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# Disposal of Dilute Pesticide Solutions

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# Disposal of Dilute Pesticide Solutions

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An extensive literature search, site visits, and interviews were conducted to evaluate disposal methods for dilute pesticide solutions generated during pesticide application equipment washing operations. The disposal methods evaluated include land cultivation, soil mounds and pits, evaporation basins, chemical treatment, carbon adsorption, activated sludge, trickling filters, and incineration. The methods were evaluated in relation to environmental safety, versatility, applicability, economics, and efficiency criteria. Given the state of the treatment method technology and the nature of the wastes and their generation, it is concluded that soil mounds could be the most readily implementable disposal method presently available.

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# DISPOSAL OF DILUTE PESTICIDE SOLUTIONS

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U.S. ENVIRONMENTAL PROTECTION AGENCY

1979

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# ABSTRACT

An extensive literature search, site visits, and interviews were conducted to evaluate disposal methods for dilute pesticide solutions generated during pesticide application equipment washing operations. Methods were evaluated in relation to environmental safety, versatility, applicability, economics, and efficiency criteria.

It was calculated that over 400,000 $m^3$ of dilute pesticide solutions are generated in the United States annually. It was determined that commercial agricultural applicators are the major source of these pesticide wastes.

The disposal methods evaluated include land cultivation, soil mounds and pits, evaporation basins, chemical treatment, carbon adsorption, activated sludge, trickling filters, and incineration. Given the state of the treatment method technology and the nature of the wastes and their generation, it is concluded that soil mounds are presently the most readily implementable disposal method available. Soil pits and evaporation basins are technically available, but present air quality problems. Adsorption is of limited utility, but is readily implementable within its limitations. Land cultivation has not been sufficiently studied in relation to dilute pesticide solutions and presents potential environmental problems. Chemical treatment can be effective, but is not applicable to all pesticides. Full-scale operating conditions have not been fully determined. Biological treatment and incineration are of use only in centralized hazardous waste management facilities.

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# CHAPTER 1

## SUMMARY AND RECOMMNDATIONS

Over 400,000 $m^3$ (100 million gal) of dilute pesticide solutions are generated in the United States each year. The primary sources of these wastes are container and equipment rinsing and washing. In the past, little attention has been paid to the proper disposal of these wastes. As a result, careless dumping often occurred resulting in water contamination, wildlife deaths, soil contamination, etc.

Dilute pesticide solutions present several disposal problems. Concentrations are generally less than the recommended application rate, based on calculations using data from available sources. Individual applicators typically generate less than 2 $m^3$ (500 gal) daily, mostly in agricultural areas. Commercial waste treatment systems are usually designed for higher flow. Many processing and disposal technologies may be either uneconomical or impractical. It is likely that future regulations will specify proper treatment and disposal of these wastes, however.

In this study, several currently used and proposed methods for disposal of dilute pesticide solutions were reviewed. The methods include:

- Soil mounds
- Chemical treatment
- Incineration
- Adsorption
- Soil pits
- Evaporation basins
- Land cultivation
- Biological treatment

All of these methods advantages and disadvantages. Soil mounds and pits for example, represent an attempt to take advantage of the strengths of land treatment while minimizing its disadvantages. Soil mounds and pits are small, lined systems that rely on soil properties to degrade pesticides while containing non-degraded pesticides or degradation products within the lined system. They require less land area and operator time than land cultivation and have a limited lifetime due to the buildup of pesticides in the soil. High pesticide concentrations can inhibit natural soil degradation mechanisms. Soil mounds and pits can still function as contain-and-concentrate systems, however. The extent of pesticide volatilization from these systems has not been fully determined yet.

Chemical treatment can yield virtually complete detoxification for many of the commonly used pesticides. For many other pesticides it is ineffective or yields toxic reaction products. Thus, chemical treatment can be a highly useful, albeit somewhat limited, treatment method. It requires more operator skill and training than the methods already discussed because of the hazardous nature of most treatment chemicals. Care must be taken to ensure proper ratios of treatment chemical to pesticide and proper selection of treatment chemical.

Incineration is highly effective at destroying all organic (except metallo-organic) pesticides. However, incineration and its support services are costly and not generally available to individual applicators. The efficacy of incineration precludes its being dropped from consideration, however. It might be possible to establish numerous central hazardous waste treatment facilities based on incineration which could be used to treat dilute pesticide solutions.

Absorption is a very effective contain-and-concentrate method for most organic pesticides. It is a proven technology readily adaptable by pesticide applicators to dilute pesticide solutions. It is ineffective with certain oil-type and inorganic pesticides, and the wastewaters require pretreatment to remove these and any insoluble suspended matter (e.g., insoluble pesticides, clays, sulfur) before treatment to prevent adsorption column fouling.

Evaporation basins also serve as contain-and-concentrate methods. In addition, some pesticide hydrolysis and photolysis can be expected to occur. These systems are frequently used by pesticide formulators and applicators. They do, however, present a hazard to local air quality due to volatilization.

Land cultivation is a simple technology, relatively inexpensive, and readily implementable in many agricultural areas. Research has shown that low concentrations of many organic pesticides will degrade in or be adsorbed by soil with little pesticide migration. However, land cultivation does not work as well with high pesticide concentrations or with certain chemical classes of pesticides. Migration to ground or surface water or volatilization can occur. The environmental fates of many pesticide degradation products are unknown.

Biological treatment can be very effective in degrading many organic pesticides. However, it is highly susceptible to up set from changes in flow rate, pesticide concentration, or type of pesticide, all of which could occur with dilute pesticide solutions. For biological treatment to be effective, sufficient contact time and a fairly uniform waste are required, and neither condition can be guaranteed by an applicator. Thus, biological treatment is not considered appropriate for individual applicators.

Table 1 presents a comparative summary of the eight treatment methods. Each method has been given a total score (based on the criteria explained in Chapter 4) and is ranked in the table according to its potential as a dilute pesticide solution method. The methods (i.e. soil mounds, chemical treatment, transport and incineration) which have the highest score have the highest potentials; biological treatment has the lowest. The use of adsorption, soil pits, evaporation basins, and land cultivation could be effective under certain conditions.

In light of the above, the following recommendations are offered:

- Ways of reducing the volume of dilute pesticide solution through improved application practices should be studied.
- Table 1 indicates that the use of a soil mound system could be the most readily implementable and effective method available for disposal of dilute pesticide solutions. Before recommending such a system for immediate and widespread use, however, soil mounds should be further evaluated in terms of liner effectiveness, pesticide volatilization, and expected useful life.
- Since evaporation basins are already widely used, research needs to be conducted into the environmental impacts of volatilization from these systems.
- Further research needs to be conducted into the extent of volatilization from soil pits.
- Land cultivation may be an alternative method for the disposal of some dilute pesticide solutions. Further research should be directed toward determining which pesticides (and at what concentrations) can be treated as well as the optimum soil conditions and loading rates necessary for effective degradation.

## TABLE 1. SUMMARY TABLE
## SCORES OF DILUTE PESTICIDE SOLUTION DISPOSAL METHODS

| | Criteria | | | | | |
|---|---|---|---|---|---|---|
| Method | Environmental Safety* | Effectiveness | Pesticide Applicability | Availability | Applicator Factor | Total |
| Soil mounds | 45 | 20 | 30 | 22 | 18 | 135 |
| Chemical treatment | 45 | 30 | 20 | 25 | 11 | 131 |
| Transport and incineration | 39 | 35 | 20 | 22 | 14 | 130 |
| Adsorption | 55 | 15 | 15 | 25 | 9 | 119 |
| Soil pits | 35 | 15 | 30 | 14 | 19 | 113 |
| Evaporation basins | 35 | 15 | 25 | 17 | 20 | 112 |
| Land cultivation | 30 | 15 | 25 | 22 | 17 | 108 |
| Biological Treatment | 40 | 25 | 15 | 15 | 4 | 99 |

*See Chapter 4. for explanation of criteria and scores.

- Further research is needed into chemical treatment to more fully identify susceptible pesticides and treatment conditions; research needs to be directed toward chemical treatment of dilute solutions of mixed pesticides.

- For all of the above treatment methods, research currently underway or planned should be expanded to include more exhaustive analyses of the fates of pesticide degradation products.

- Since the advantages, disadvantages, and limitations of carbon adsorption are largely known, adsorption should be demonstrated on actual dilute pesticide solutions from commercial applicators.

# CHAPTER 2

# INTRODUCTION

The increasing awareness of the health and environmental problems associated with pesticides has spawned a reassessment of all phases of pesticide production and use. One aspect of pesticide use that has generally been overlooked in the past is the disposal of wastewaters from pesticide container and application equipment cleaning operations. All of these wastewaters contain pesticides in varying concentrations but their disposal has prompted little concern in the past because the liquors were generally considered dilute and, therefore, innocuous.

## PESTICIDE USE AND WASTE QUANTITIES

The quantities of such wastewaters are far from insignificant. These wastewaters, hereafter called dilute pesticide solutions, are generated during several activities: pesticide container rinsing, spray equipment tank rinsing, and general equipment washing. They may also include unwanted dilute spray mixtures. Estimates of the quantities of dilute pesticide solutions produced in 1966 were:

- 22,740 $m^3$ ($6 \times 10^6$ gal) of container rinsate
- 379,000 $m^3$ ($100 \times 10^6$ gal) of aerial application equipment washwater
- 22,740 $m^3$ ($6 \times 10^6$ gal) of custom application equipment washwater (1).

These yield a total of 424,480 $m^3$ ($112 \times 10^6$ gal) of dilute pesticide solutions for 1966. This quantity may have increased substantially since 1966 because the total acreage treated with pesticides and the quantity of pesticides applied by custom applicators have increased significantly (2, 3). It has been estimated that each application airplane and ground applicator rig produces from 20 to 230 ℓ (5 to 60 gal) of wastewater per day (4).

There has been little research conducted to date either to determine the concentration of these dilute pesticide solutions or to estimate the total quantity of pesticides in the annual production of dilute pesticide solutions. The variety of pesticide formulations (granules, powders, soluble salts, liquids), mixing ratios, and application methods make generalization very difficult. Dilute pesticide solutions are, by definition, at concentrations equal to or below recommended application rates. These rates vary widely; documented concentrations of pesticides in container rinsate range up to as high as 14,800 ppm (5). Researchers at Oregon State University found pesticide concentrations of 500 ppm in wastewater from a container cleaning process (6). Application equipment washwaters have not been sufficiently characterized to determine average or typical pesticide concentrations.

Be that as it may, Federal guidelines specify that pesticide container rinsate be treated as waste pesticide for disposal purposes (Federal Environmental Pesticide Control Act). The definition of pesticide includes pesticide-containing wastewaters. Based on such criteria, dilute pesticide solutions, generally dismissed as trivial in the past, become a real and pressing hazardous waste disposal problem.

Before considering disposal alternatives, it is appropriate to briefly look at pesticide users to determine who will be faced with the need to treat or dispose of dilute pesticide solutions, as well as what types of pesticides might be involved. Table 2 lists 50 of the leading pesticides used in the United States in 1976, production estimates, and estimates of how use of the pesticide was distributed among the various user groups. Since general discussions of pesticide use and disposal usually deal more with types or classes of pesticides (based on chemical similarities) than with individual compounds, Table 3 breaks down the fifty pesticides into general types, and Tables 4 and 5 break down the use of these pesticide types by their distribution among various user groups and within each user group.

As might be expected, the primary use of pesticides is for agriculture, including use by both farmers and custom applicators. Slightly more than 2/3 of all pesticides (3/4 of the insecticides and herbicides) are used on cropland. The next largest use, by urban, industrial, and commercial building pest control operators, comprises 18 percent of overall pesticide use and 1/3 of the fungicide use. Home and garden users are next, followed by the Federal government. These figures do not agree precisely with the newest available information as presented in "Pesticide Usage Survey of Agricultural, Governmental, and Industrial Sectors in the United States, 1974," Office of Pesticide Programs, EPA, but the conclusion, that agricultural pesticide use exceeds all other uses, is the same.* In fact, this latest information places the figure at 94 percent.

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*Report unavailable at this writing but contents highlighted in Reference 10.

## TABLE 2. FIFTY OF THE MOST COMMON U.S. INSECTICIDES, HERBICIDES, AND FUNGICIDES*

| | | Use (%)‡ | | | |
|---|---|---|---|---|---|
| Pesticide | 1976 Production ($10^3$ t/yr AI)† | Agricultural | Home & Garden | Industrial/ Commercial | Government |
| **Insecticides and Rodenticides** | | | | | |
| Aldicarb | 0.5-2 | 99 | <1 | <1 | <1 |
| Carbaryl | 22-45 | 76 | 14 | 4 | 6 |
| Carbofuran | 2-6 | 99 | <1 | <1 | <1 |
| Chlordane | 6-13 | 20 | 33 | 43 | 4 |
| Chloropicrin | 2-6 | | | | |
| Diazinon | 2-6 | 43 | 28 | 17 | 12 |
| Dichlorvos | 0.5-2 | <1 | 15 | 70 | 15 |
| Disulfoton | 2-6 | 98 | <1 | <1 | 1 |
| Endosulfan | 0.5-2 | 85 | 5 | 5 | 5 |
| Ethion | 0.5-2 | 99 | <1 | <1 | <1 |
| Fensulfothion | 0.5-2 | 99 | <1 | <1 | <1 |
| Heptachlor | 2-6 | 75 | <1 | 25 | <1 |
| Lindane and BHC | 0.5-2 | 70 | 15 | 15 | <1 |
| Malathion | 13-22 | 31 | 31 | 25 | 13 |
| Methoxychlor | 2-6 | 10 | 40 | 40 | 10 |
| Methyl parathion | 13-22 | 99 | <1 | <1 | <1 |
| Monocrotophos | 2-6 | 99 | <1 | <1 | <1 |
| Naled | 0.5-2 | 25 | 25 | 25 | 25 |
| Parathion | 6-13 | 99 | <1 | <1 | <1 |
| Phorate | 2-6 | 99 | <1 | <1 | <1 |
| Ronnel | 0.5-6 | 20 | <1 | 60 | 20 |
| Toxaphene | 13-22 | 98 | <1 | 1 | <1 |
| | Weighted Avg | 74 | 10 | 12 | 4 |
| **Herbicides** | | | | | |
| Alachlor | 6-13 | 99 | <1 | <1 | <1 |
| Atrazine | >45 | 96 | 1 | 2 | 1 |
| Bromacil | 2-6 | 13 | <1 | 77 | 10 |
| Chloramben | 6-13 | 99 | <1 | <1 | <1 |
| 2,4-D | 6-13 | 76 | 6 | 12 | 6 |
| Dalapon | 0.5-2 | 15 | 5 | 15 | 65 |
| Dicamba | 0.5-2 | 40 | 10 | 40 | 10 |
| Diuron | 2-6 | 37 | <1 | 57 | 6 |
| Methanearsonics (MSMA, DSMA) | 22-45 | 66 | 8 | 21 | 5 |
| Picloram | 0.5-2 | 35 | <1 | 65 | <1 |
| Propachlor | 6-13 | 99 | <1 | <1 | <1 |
| Propanil | 2-6 | 99 | <1 | <1 | <1 |
| Silvex | 0.5-2 | 99 | <1 | <1 | <1 |

TABLE 2 (Continued)

| Pesticide | 1976 Production ($10^3$ t/yr AI)† | Use (%)‡ Agricultural | Home & Garden | Industrial/ Commercial | Government |
|---|---|---|---|---|---|
| **Herbicides** | | | | | |
| Simazine | 2-6 | 20 | <1 | 80 | <1 |
| 2,4,5-T | 2-6 | 60 | <1 | 40 | <1 |
| Thiocarbamates (Butylate, EPTC) | 13-22 | 75 | 25 | <1 | <1 |
| Trifluralin | 6-13 | 98 | 1 | 1 | <1 |
| | Weighted Avg | 74 | 4 | 18 | 4 |
| **Fungicides** | | | | | |
| Benomyl | 2-6 | 70 | 30 | <1 | <1 |
| Captafol | 0.5-2 | 70 | 30 | <1 | <1 |
| Captan | 6-13 | 62 | 37 | <1 | <1 |
| Dodine | 0.5-2 | 70 | 30 | <1 | <1 |
| Ferbam | 0.5-2 | 50 | 50 | <1 | <1 |
| Folpet | 0.5-2 | 65 | 35 | <1 | <1 |
| Maneb | 2-6 | 79 | 21 | <1 | <1 |
| Metham | 2-6 | 75 | 25 | <1 | <1 |
| Pentachlorophenol | 13-22 | <1 | 3 | 97 | <1 |
| Trichlorophenol | 6-13 | <1 | <1 | 99 | <1 |
| Zineb | 0.5-2 | 85 | 15 | <1 | <1 |
| | Weighted Avg | 46 | 21 | 33 | <1 |
| | Overall Avg | 69 | 10 | 18 | 3 |

---

* Von Rumker, R. et al. Production, distribution, use, and environmental impact potential of selected pesticides, 1974 (7).

U.S. International Trade Commission. Synthetic organic chemicals United States production, and sales, 1976 (8).

Farm Chemicals Handbook, 1978 (9).

† Metric ton per year active ingredient (AI). Production figures are taken directly or are estimated based on information from references 7 and 8.

‡ Use estimates are taken directly or are estimated based on information from references 7 and 9.

## TABLE 3. FIFTY COMMON PESTICIDES IN THE U.S. BY TYPE WITH APPROXIMATE SHARE OF THE MARKET (%)*†

Chlorinated Hydrocarbon (12)

- Chlordane
- Endosulfan
- Heptachlor
- Lindane and BHC
- Methoxychlor
- Toxaphene

Carbamates (7)

- Aldicarb
- Carbaryl
- Carbofuran

Organic Phosphorus (21)

- Diazinon
- Dichlorovos
- Disulfoton
- Ethion
- Fensulfothion
- Malathion
- Methyl Parathion
- Monocrotophos
- Naled
- Parathion
- Phorate
- Ronnel

Triazines (7)

- Atrazine
- Simazine

Chlorophenoxy Acids (5.5)

- 2,4-D
- 2,4,5-T
- Silvex

Methanearsonics (4.5)

Organic Nitrogen (10)

- Alachlor
- Benomyl
- Dodine
- Propachlor
- Propanil

Benzoic acid derivatives (4.5)

- Chloramben
- Dicamba
- Picloram

Dinitro aromatics (2.5)

- Trifluralin

Uracils (3.5)

- Bromacil
- Diuron

Chlorinated alkyl acids (1)

- Dalapon

Chlorophenols (6)

- Pentachlorophenol
- Trichlorophenol

Dicarboxamides (4.5)

- Captafol
- Captan
- Folpet

Dithiocarbamates (5.5)

- Ferbam
- Maneb
- Metham
- Zineb

Thiocarbamates (3.5)

Miscellaneous (2)

- Chloropicrin

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* Von Rumker, R. et al. Production, distribution, use, and environmental impact potential of selected pesticides, 1974 (7).
Farm Chemicals Handbook, 1978 (9).

† Based on the figures in Table 2.

TABLE 4. PESTICIDE USE BY TYPE OF PESTICIDE (%)*

| Pesticide Type | Agricultural | Home & Garden | Industrial/ Commercial | Government | Total |
|---|---|---|---|---|---|
| Chlorinated hydrocarbon | 62 | 16 | 19 | 3 | 100 |
| Carbamates | 85 | 9 | 2.5 | 3.5 | 100 |
| Organic phosphorus | 73 | 9 | 12 | 6 | 100 |
| Triazines | 77 | <1 | 22 | <1 | 100 |
| Chlorophenoxy acids | 75 | 3 | 19 | 3 | 100 |
| Methanearsonics | 66 | 8 | 21 | 5 | 100 |
| Organic nitrogen | 92 | 8 | <1 | <1 | 100 |
| Benzoic acid derivatives | 75 | 2 | 21 | 2 | 100 |
| Dinitro aromatics | 98 | 1 | 1 | <1 | 100 |
| Uracils | 25 | <1 | 67 | 8 | 100 |
| Chlorinated alkyl acids | 15 | 5 | 15 | 65 | 100 |
| Chlorophenols | <1 | 2 | 98 | <1 | 100 |
| Dicarboxamides | 64 | 35 | <1 | <1 | 100 |
| Thiocarbamates | 75 | 25 | <1 | <1 | 100 |
| Dithiocarbamates | 74 | 25 | <1 | <1 | 100 |

---

*Based on the figures in Table 2.

TABLE 5. PESTICIDE USE DISTRIBUTION WITHIN EACH USER SEGMENT (%)*

| Pesticide Type | Agricultural | Home & Garden | Industrial/ Commercial | Government |
|---|---|---|---|---|
| Chlorinated hydrocarbon | 10 | 18 | 12 | 10 |
| Carbamates | 9 | 6 | 1 | 8 |
| Organic phosphorus | 24 | 20 | 14 | 38 |
| Triazines | 8 | <1 | 8 | 2 |
| Chlorophenoxy acids | 6 | 2 | 6 | 5 |
| Methanearsonics | 4 | 4 | 5 | 7 |
| Organic nitrogen | 14 | 8 | <1 | <1 |
| Benzoic acid derivatives | 5 | 1 | 5 | 3 |
| Dinitro aromatics | 4 | <1 | <1 | <1 |
| Uracils | 1 | <1 | 13 | 9 |
| Chlorinated alkyl acids | <1 | <1 | 1 | 18 |
| Chlorophenols | <1 | 1 | 34 | <1 |
| Dicarboxamides | 4 | 16 | <1 | <1 |
| Thiocarbamates | 5 | 9 | <1 | <1 |
| Dithiocarbamates | 6 | 14 | <1 | <1 |
| Total | 100 | 100 | 100 | 100 |

---

*Based on the figures in Table 2.

Government, and home and garden users are not considered in evaluating the various dilute pesticide solution disposal options in this report. The government is not a particularly major pesticide user, shows no particular predilection for any pesticide or pesticide type (except Dalapon) different from the other user groups (see Table 2), and will be subject to any disposal regulations imposed on other users. Although overall consumption of pesticides (especially herbicides) may be significant, use by individual households may not amount to much over a few kilograms/household/yr. Consequently, the amount of dilute pesticide solution generated by each home user would be minuscule.

Urban, industrial, and commercial pest control operators consume nearly 20 percent of the United States pesticide production, a relatively small amount compared to the agricultural use. Furthermore, the circumstances of urban use and waste disposal do not lend themselves to the overall review of the scope of this study. Consideration of urban pest controller dilute pesticide solutions requires a different approach from agricultural dilute pesticide solutions because the two user segments face completely different disposal problems and constraints. No effort was made in this study to assess and evaluate the disposal options available exclusively to the industrial/commercial user segment. Wherever a particular agricultural disposal option may also be appropriate for an urban pest controller, it is noted. This report concentrated on the major pesticide use segment: agriculture.

Agricultural pesticide use is the principal source of dilute pesticide solutions. Agricultural pesticide use exceeds other uses combined by a 2:1 ratio (some reports put the figure as high as 85 to 90 percent (10-11). Moreover, larger quantities of rinse and washwater are needed because of the application equipment involved. Consequently, the volume of dilute pesticide solution from agricultural uses exceeds the volume from all other sources combined by more than a 2:1 margin. Thus, on volume alone, agricultural dilute pesticide solutions are the major problem.

## PAST DISPOSAL PRACTICES

In the past, many agricultural applicators simply dumped waste pesticides on the ground or into nearby water bodies because they had no other disposal systems that could handle dilute pesticide solutions economically (12). Such disposal practices pose threats of pesticide contamination to ground and surface water, air quality, public health, and livestock and crops in the disposal area. Several fish kills have been attributed to uncontrolled runoff from pesticide equipment wash pads (personal communication, J. D. Linn, California Department of Fish and Game), container disposal, and runoff from fields (4, 13-15). On the other hand, the large volume of water may interfere with or preclude many conventional disposal methods applicable for other waste pesticides (e.g., incineration or encapsulation) without extensive waste stream pretreatment.

## PROJECT OBJECTIVES

The overall pupose of this study is to evaluate the state of the art of disposal methods in use or proposed for dilute pesticide solutions. Specific objectives are to review and evaluate present and proposed disposal methods; assess the cost, use potential, and effectiveness of the proposed methods; and to provide recommendations for further study and potential demonstration. The methods addressed in this study are:

- Land cultivation
- Soil mounds and pits
- Evaporation basins and lagoons
- Chemical treatment
- Physical treatment (adsorption, reverse osmosis)
- Biological treatment (trickling filter, activated sludge)
- Incineration

In addition, the report briefly covers means for reducing the volume of dilute pesticide solutions through improved application practices or reuse.

The following assumptions about the character of dilute pesticide solutions are used to assess the disposal methods:

- Most dilute pesticide solutions (by volume) are generated by agricultural applicators in rural areas.

- Approximately 90 percent of this waste is from rinsing and washing aerial application equipment (11, 16).

- Given a total annual volume of 424,480 $m^3$ (112 x $10^6$ gal) and approximately 1,100 commercial crop dusting and spraying establishments, the average annual quantity of dilute pesticide solution per applicator is 385 $m^3$ (102,000 gal) (17). Approximately 77 percent of all commercial agricultural pesticide applicators operate in areas where crops are grown much of the year (the south and southwest, year-round growing season: the plains states, winter grains) (17). Therefore, a 10-mo working year (225 days) is a reasonable assumption, giving an average daily dilute pesticide solution generation rate of 1.7 $m^3$ (450 gal) per applicator.

The following criteria were used to select and evaluate potential disposal methods:

- The disposal method must be environmentally safe and not contribute to the degradation of air or water quality.
- Unless dilute pesticide solutions are collected and stored for subsequent transport to a central processing facility, the disposal system must be located at or near (within 5 mi) the waste generation site.
- The disposal method must disrupt normal application operations as little as possible.
- The disposal method should be inexpensive enough to be feasible for the smallest application establishments.
- The disposal method should be adaptable to any climatological or geographical area in the United States where agriculture is a major practice.
- If possible, at least one disposal method should be amenable to application in urban settings.
- The disposal method should not require highly skilled operators.
- The disposal method should be capable of handling a wide range of pesticide types, formulations, and concentrations with highly variable flow rates.

The relative weights for these criteria are discussed in Chapter 4.

One option that is not addressed as an option per se in this report is the collection of dilute pesticide solutions from all applicators in a given area for transport to a central waste treatment facility or hazardous waste landfill. The advantages and disadvantages of central facilities will be discussed in the incineration section.

Although any of the methods discussed herein could be employed at a central waste processing facility, the nature of incineration (as presented in the following chapter) precludes its use by individual applicators. Thus, incineration is only suitable for use at central facilities. This should become clearer in the following discussions.

# CHAPTER 3

# DISPOSAL METHODS FOR DILUTE PESTICIDE SOLUTIONS

## OVERVIEW

There are three basic goals in dilute pesticide solution disposal: containment, detoxification, and volume reduction. Detoxification is of primary importance. If a hazard-free effluent can be produced, volume will no longer be a critical factor. Complete detoxification is seldom achievable in reality, so it becomes necessary to reduce the volume of hazardous materials generated to a more manageable level and to contain the material in a monitored disposal area.

As noted in the introduction, dilute pesticide solutions have not always been considered hazardous. Rinsate and washwater were seldom collected. If they were, they were either buried nearby or taken to a landfill or dump. Sometimes, dilute pesticide solutions from washdown pads were allowed to run into ditches or creeks near the pad, from which they ultimately could contaminate water supplies (Figure 1).

Because of their unique nature (i.e. large volume, low concentration, many generators) many disposal methods traditionally applied to hazardous solid and liquid wastes are not always applicable. Given the immediacy of the problem, it is imperative to identify disposal methods that are currently available or can readily be developed and adapted to dilute pesticide solutions without delay.

A variety of methods have been suggested, proposed, or tested for treating dilute pesticide solutions. These run the technological gamut from simple land cultivation to exotic technologies such as microwave plasma destruction (18). The most commonly discussed methods and those evaluated in this report are:

- Land disposal (land cultivation, soil mounds and pits)
- Evaporation basins
- Chemical treatment
- Adsorption
- Biological treatment
- Incineration.

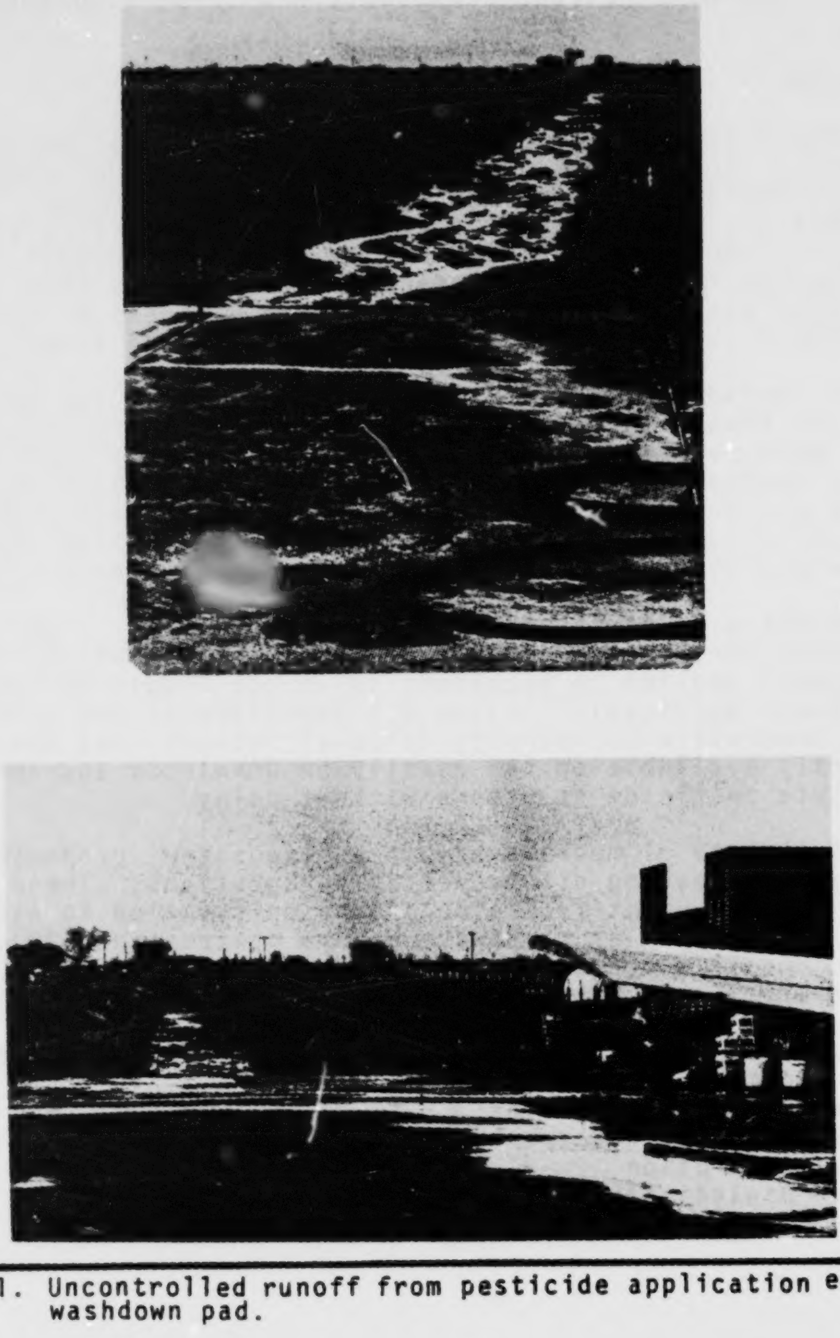

Figure 1. Uncontrolled runoff from pesticide application equipment washdown pad.

Although all are theoretically applicable, there has been little or no field-scale testing of most of these methods with dilute pesticide solutions. Consequently, operating data for evaluation are often lacking. The characteristics of the industries generating dilute pesticide solutions, the character of the wastes themselves, and experience with these methods with other wastes must be used in evaluations where actual field data are unavailable.

## LAND DISPOSAL

Land disposal relies on the natural physical, chemical, and biological properties of soil to adsorb, immobilize, and decompose pesticides. There are several disposal techniques which attempt to take advantage of these mechanisms (e.g. land cultivation, soil mounds and pits).

The mechanisms of soil treatment include:

- Volatilization
- Photochemical degradation
- Adsorption onto clay, silt, and organic matter
- Adsorption-catalyzed hydrolysis and oxidation
- Microbial degradation.

Several attempts have been made to quantify the contributions made by each of these mechanisms to the overall behavior of pesticides in soil (19-21). None of the models thus developed work especially well because of the wide range of natural soil conditions and the differences in chemical behavior among the different pesticides. However, a knowledge of the mechanisms is useful in assessing the applicability of land disposal in a specific situation.

Volatilization has recently been given a much greater role in the loss of pesticides from the soil than previously believed (22-25). Several researchers have stated that volatilization is the major pathway of loss for certain pesticides (23, 25). Volatilization rates from plant and moist soil surfaces for the more volatile pesticides can approach ninety percent within three days of application (26). When the pesticides are placed below the soil surface, volatilization continues, but at a much reduced rate (13, 22, 25). A detailed discussion of pesticide volatilization rates is beyond the scope of this report, but an estimate of the maximum volatilization fluxes is useful in assessing one of the environmental impacts of land disposal.

When a pesticide is placed below the soil surface, loss by volatilization involves movement of the pesticide upward to the soil-atmosphere interface and vaporization into the atmosphere. The actual volatilization rate is dependent upon the rate of movement of the pesticide to the soil surface (22, 25). In the absence of evaporating water, the volatilization rate depends on the rate of movement of the pesticide to the soil surface by diffusion. When water evaporates from the soil surface, an upward movement of water results, and any pesticide not adsorbed in the soil solution moves toward the surface by mass flow with the evaporating water. Thus, there are two general mechanisms whereby pesticides move to the evaporating surface: diffusion and mass flow in evaporating water. For a soil disposal system, either or both transport mechanism will be important depending upon the particular pesticide and on the amount of water present in the system.

When water evaporates from the soil surface, transport of pesticides by mass flow in the evaporating water will usually be the dominant transport mechanism. Mass flow processes are generally much more rapid than diffusion controlled processes. Transport to the soil surface in evaporating water is often referred to as the "wick effect." When there is mass flow of pesticides to the soil surface, the maximum pesticide volatilization flux can be estimated using the following equation (22, 27):

$$J_p = CJ_w \qquad (1)$$

where: $J_p$ = the pesticide vapor flux in mass/area/time

$C$ = the pesticide concentration in solution

$J_w$ = the water flux

The concentration of pesticide in solution, C, is a function of adsorption of the pesticide by the soil and of chemical and microbial degradation. The maximum volatilization flux from a soil mound would be expected with a persistent compound and after the system had been in operation long enough for soil adsorption processes to come to equilibrium. Thus, for a compound like lindane, a relatively persistent insecticide with a water solubility of 10 ppm, the maximum volatilization flux that one could expect from the surface of a soil mound would be

$$J_p = 10 \text{ ppm} \times J_w \qquad (2)$$

or 10 μg of lindane evaporating per cm of water evaporating per $cm^2$ of soil surface per unit time or 1.0 kg/ha/time/cm water.

Little or no volatilization of the parent compound would be expected from compounds subject to rapid decomposition in soils. For example, the organophosphate insecticide parathion is subject to relatively rapid microbial and chemical decomposition in soil; most of the parathion would be expected to be degraded before reaching the soil surface. Strongly adsorbed compounds and many compounds of low water solubility would exhibit little volatilization flux. For instance, the herbicides paraquat and trifluralin are both strongly adsorbed by soil particles and would not move appreciably in evaporating water. Study of the volatilization behavior of pesticide degradation products has not been as thorough as that of pesticides.

When diffusion through the soil is the mechanism controlling pesticide transport, the volatilization flux will generally be lower than that due to mass flow because diffusion rates are usually substantially lower than water movement rates. Exceptions would be when the pesticide is insoluble in water and little movement with the water would be expected. It is difficult to present general equations predicting volatilization flux due to diffusion controlled transport because of the large number of soil and pesticide factors contributing to the flux (28).

At the present time there are no Federal regulations or guidelines concerning air emissions of pesticides from treatment and disposal facilities, although establishment of such is a distinct possibility. Based on the above calculations, an adsorption-saturated soil disposal system containing a persistent pesticide in an area with a high evaporation rate (e.g., 200 cm/yr) would have emissions of approximately 200 kg/ha/yr or 6.5 mg/sec/ha. The concentration of the pesticide in the air above the site would depend on the atmospheric diffusion, keeping in mind that if diffusion is slight, concentrations will increase at the soil surface and the emission rate will decrease. Further research is needed to establish the emission rates of a non-persistent pesticide from a non-saturated soil system for an expected range of evaporation rates. Research is also needed to establish how pesticide emissions from a disposal site in an agricultural area would compare with normal atmospheric pesticide burdens from crop spraying. The disposal site could represent a continuing source of pesticides to the air as opposed to the seasonal "slug" additions of pesticides from crop use. On the other hand, regular emissions from disposal sites may be significantly lower than the amounts of pesticides added to the air during agricultural operations (29-30).

Under ideal conditions, most organic pesticides are subject to photolysis (31-32). It is doubtful, however, that photodecomposition of pesticides in soil has much practical significance (31). To begin with, only pesticides on the soil surface would be susceptible. Since most other soil degradation mechanisms are enhanced by soil incorporation, it is usually not advisable to leave the pesticide on the soil surface where it must compete with other substances for the available solar energy and where there is a greater potential for runoff. Radiant energy is strongly sorbed by soil and thus is not always available even to surface pesticides (31). Consequently, photolysis plays only a minor role in the degradation of pesticides in the soil.

Adsorption, however, is the major factor in determining whether and how far pesticides will move in the soil. Table 6 lists the relative mobilities of several pesticides in soil. In general, nonionic pesticides are adsorbed more strongly than anionic pesticides (32-33). Cationic pesticides (e.g. diquat and paraquat) are strongly adsorbed by soils (Personal communication, Dr. W. J. Farmer, University of California to J. R. Marsh, SCS Engineers). Aside from the chemical structure of the pesticides, soil properties also strongly influence adsorption. Clay and organic matter content tend to be highly correlated with pesticide adsorption (24, 32). Sandy soils favor pesticide mobility. Adsorption is also more favorable in dry than wet soil (34). Water competes successfully with pesticides for available adsorption sites. Research is needed to establish the effect of the water-pesticide ratio on adsorption. The shear bulk of the water present in dilute pesticide solutions means there will be ample opportunity for pesticides to desorb and for relatively large amounts of pesticide to be present in solution.

In general, adsorption appears to be a major mechanism in pesticide retention in soils. A number of studies have demonstrated the low mobility of many pesticides in non-sandy soils (6, 24, 33, 35-40). Adsorption becomes especially important when considering land cultivation as a disposal method, because many land cultivation sites are unlined. Site selection should be based in part on soil characteristics which would retard the horizontal and vertical movement of pesticides through the soil (e.g. cation exchange capacity, percent clay, organic matter content, soil, pH).

Pesticide degradation in soils is primarily by microbial or chemical means (32). Most studies have failed to

## TABLE 6. RELATIVE MOBILITY OF PESTICIDES IN SOILS*†

| Immobile | | Slightly Mobile | Mobile |
|---|---|---|---|
| Aldrin | | Atrazine | 2,4-D |
| Chlordane | | Simazine | 2,4,5-T |
| DDT | | Prometryne | MCPA |
| Dieldrin | | Azinophosmethyl | Picloram |
| Endrin | | Carbophenthion | Fenac |
| Heptachlor | | Diazinon | |
| Toxaphene | | Ethion | |
| TDE | | Methyl parathion | |
| Lindane | ↔ | Lindane | |
| Heptachlor epoxide | ↔ | Heptachlor epoxide | |
| Trifluralin | | Parathion | |
| | | Phorate | |
| | | Diuron | |
| | | Monuron | |
| | | Linuron | |
| | | CIPC | |
| | | IPC | |
| | | EPTC | |
| | | Pebulate | |

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* Working Group on Pesticides. Ground disposal of pesticides, 1970 (41).

† Mobilities are based on soil thin-layer chromatography - mobile compounds move between $R_f$ 1.0 - 0.65, slightly mobile 0.64 - 0.10, and immobile 0.09 - 0.00. ($R_f$ = "relative to fructose")

differentiate between these two mechanisms and the data are often inconclusive. Consequently, it is often difficult to assess the relative significance of the two mechanisms. It is obvious that both contribute significantly to pesticide degradation (42).

Any pesticide subject to hydrolysis and oxidation in water is susceptible to the same chemical degradation reactions in moist soils. The reactions are often faster in soil since the pesticides can be catalyzed by adsorption on the surface of organic particles, clays, and iron and aluminum oxides (34). In addition to adsorption and soil moisture, soil pH also plays an important role; degradation of many pesticides may be twice as rapid in alkaline than acid or neutral soils (43).

When pesticides are initially applied to a soil system, the natural soil microflora population may decline (1). Repeated pesticide additions at low rates, as with dilute pesticide solutions, tend to acclimate the microorganisms and degradation rates increase. Some pesticides have been considered nonbiodegradable because specific microorganisms able to utilize those pesticides as a sole energy source have not been isolated. Frequently, however, these pesticides can be degraded when placed in a mixed culture of soil microorganisms. It is apparent that the soil microorganisms are more versatile and complex than the limited laboratory tests performed to date have indicated.

However, test results often indicate a need for supplementary nutrients or simple energy sources in a soil system used for pesticide disposal. These could be provided by additions of commercial fertilizers and easily decomposable organic amendments such as glucose or municipal wastewaters. This last source suggests the possibility of using the same land disposal site for dilute pesticide solutions and municipal wastewaters. Research has not revealed any unexpected or uncontrollable adverse effects apart from those normally associated with land cultivation of municipal wastewaters (38).

All of these mechanisms indicate that given proper site selection and solution loading rates, most pesticides from dilute pesticide solutions will not migrate through the soil appreciably and will degrade on site. However, pesticides, particularly persistent types or degradation products, can accumulate in the soil if the application rate exceeds the degradation rate, ultimately rendering the site useless for effective disposal. High concentrations of pesticides in soil (10 to 20,000 ppm) tend to retard degradation and increase the potential for migration (44).

## Land Cultivation

Simply stated, land cultivation is the emplacement of wastes within the plow layer of the soil (45). The objective is to achieve thorough mixing of the pesticide wastes in the plow layer where they will be subject to chemical and aerobic microbial degradation. At the same time, movement of the pesticides off site through runoff or by vectors is controlled and minimized through proper site selection and construction and waste application.

Land cultivation has been used for industrial and municipal wastes for several years. However, the technology is still developing and exact guidelines regarding site selection, techniques, and amenable wastes are not always available. In practice it has been a mixed success. One recent study examined several land cultivation sites and found no evidence of ground or surface water degradation (45). Other studies have been more negative but, on closer examination, the sites in these studies usually did not, strictly speaking, practice land cultivation (46). For land cultivation to work, strict site selection and waste application criteria must be developed and followed. Where attempts have been made to do this, the results have been largely positive (45).

In general, site selection is based on a number of factors. The site cannot be in a flood plain or located so that runoff would imperil surface water quality. The site hydrogeology should be such that contamination of groundwater by leachate is at least held to a minimum. Site soils should have those characteristics (previously discussed) most favorable to degrading or retaining the wastes on-site.

The amount of land needed depends on the quantity and quality of dilute pesticide solutions and may have to be determined experimentally for a given site. It might be feasible to tie loading rates in with pesticide application rates. For instance, dinoseb can be applied to citrus at rates up to 10 lb a.i./acre four times per year presumably without adversely affecting the environment (47). A land cultivation loading rate not exceeding this application rate (40 lb/ac/yr) should also be safe. Spreading rates could be based on the types and concentrations of pesticides in the dilute pesticide solutions. For 1.7 $m^3$ (450 gal)/day of washwaters containing dinoseb at 1,000 ppm, 8.5 ha (21 ac) would be needed to handle one year's waste. Of course, this is a rough estimate based on use rates; actual field tests could reduce the quantity substantially.

Ideally, the land should be located near the source of the dilute pesticide solutions, assuming other site selection criteria can be met. For aerial applicators, the unused land along runways might be well-suited. Other applicators might be able to use marginal land near their base or several applicators could use a centrally located site. Local land availability and site suitability will determine the feasibility of land cultivation.

To control runoff due to incident precipitation or excess dilute pesticide solution, a series of collection ditches and berms is usually constructed around a site (Figure 2). Such a system prevents contaminated water from leaving the site as surface runoff and collects it in a sump from which it can be reapplied to the site as weather conditions warrant (45).

Equipment needs are limited to hardware to get the dilute pesticide solution onto the soil surface and mixed into the soil. A variety of techniques and equipment can be used to accomplish this. The dilute pesticide solutions can be spread on the soil surface by spray irrigation or tank truck or wagon and then disked into the soil (44), or the wastewater can be injected and mixed directly into the soil in one operation (6, 45). Figure 3 illustrates one example of this operation whereby dilute pesticide solution is pumped from the tank to the blades or chisels of a subsoiler. The wastewater is injected uniformly at about 30 cm (12 in) below the surface. Subsurface injection has an advantage over spreading in that the pesticides are not left on the soil surface where they can readily volatilize, be blown away, wash off, or affect wildlife, but are immediately incorporated into the soil where these problems are minimized.

Subsurface injection requires a minimum of personnel (1 to 2) and probably no more than an hour or two per day during the application season, assuming the disposal site is near the generation site. Maintenance would be limited to routine tractor and pump maintenance. The skills required are readily available in any farming community.

One of the questions faced in land cultivation is whether or not to plant vegetation on the disposal site. The advantages are:

- The site is more aesthetically pleasing.
- Vegetation reduces wind and water erosion.
- Vegetation aids in water removal through evapotranspiration.
- Vegetation tends to tie up some pesticides through plant uptake.

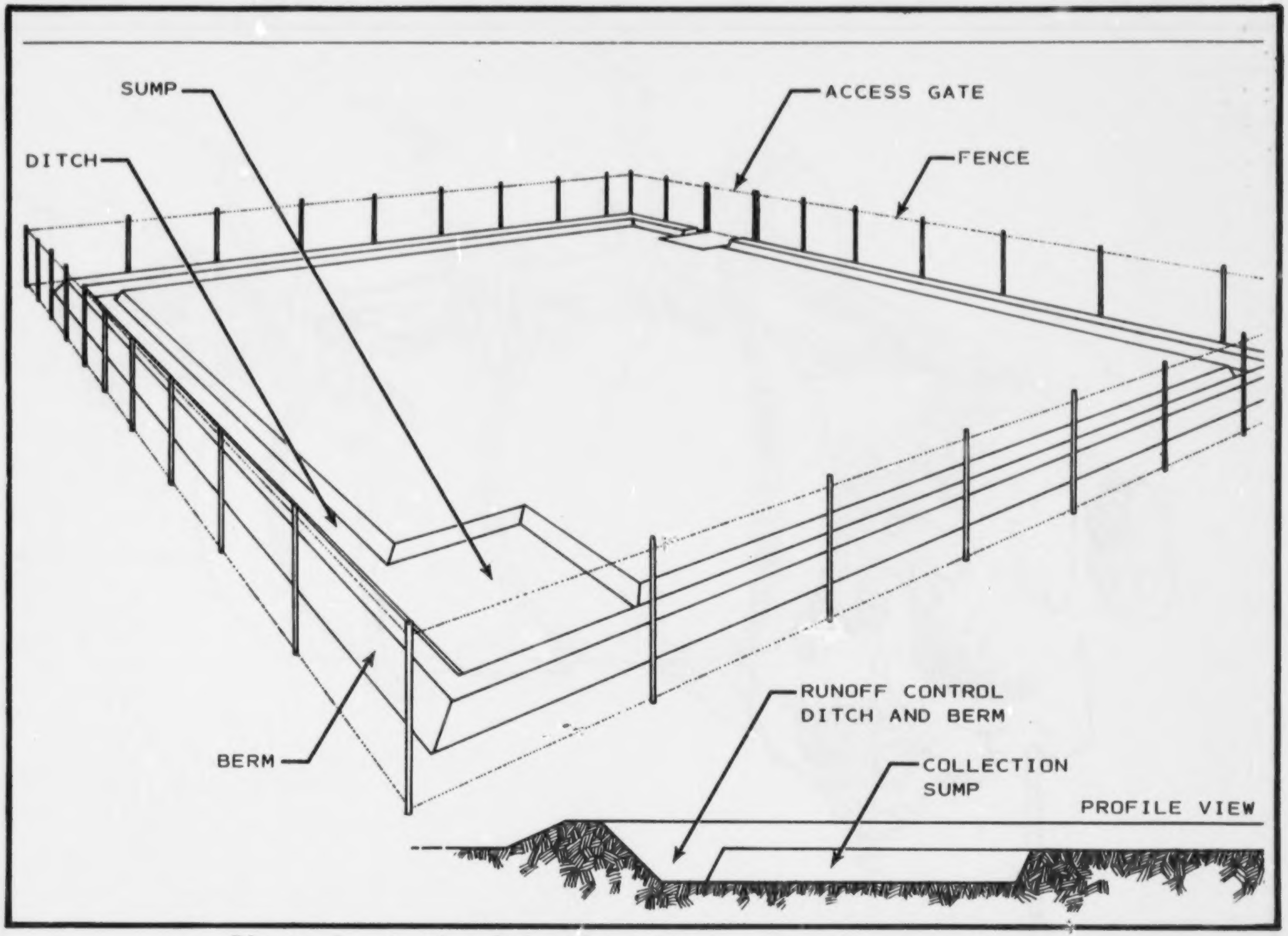
SUMP
DITCH
ACCESS GATE
FENCE
BERM
RUNOFF CONTROL DITCH AND BERM
COLLECTION SUMP
PROFILE VIEW

Figure 2. Land cultivation site runoff control system.

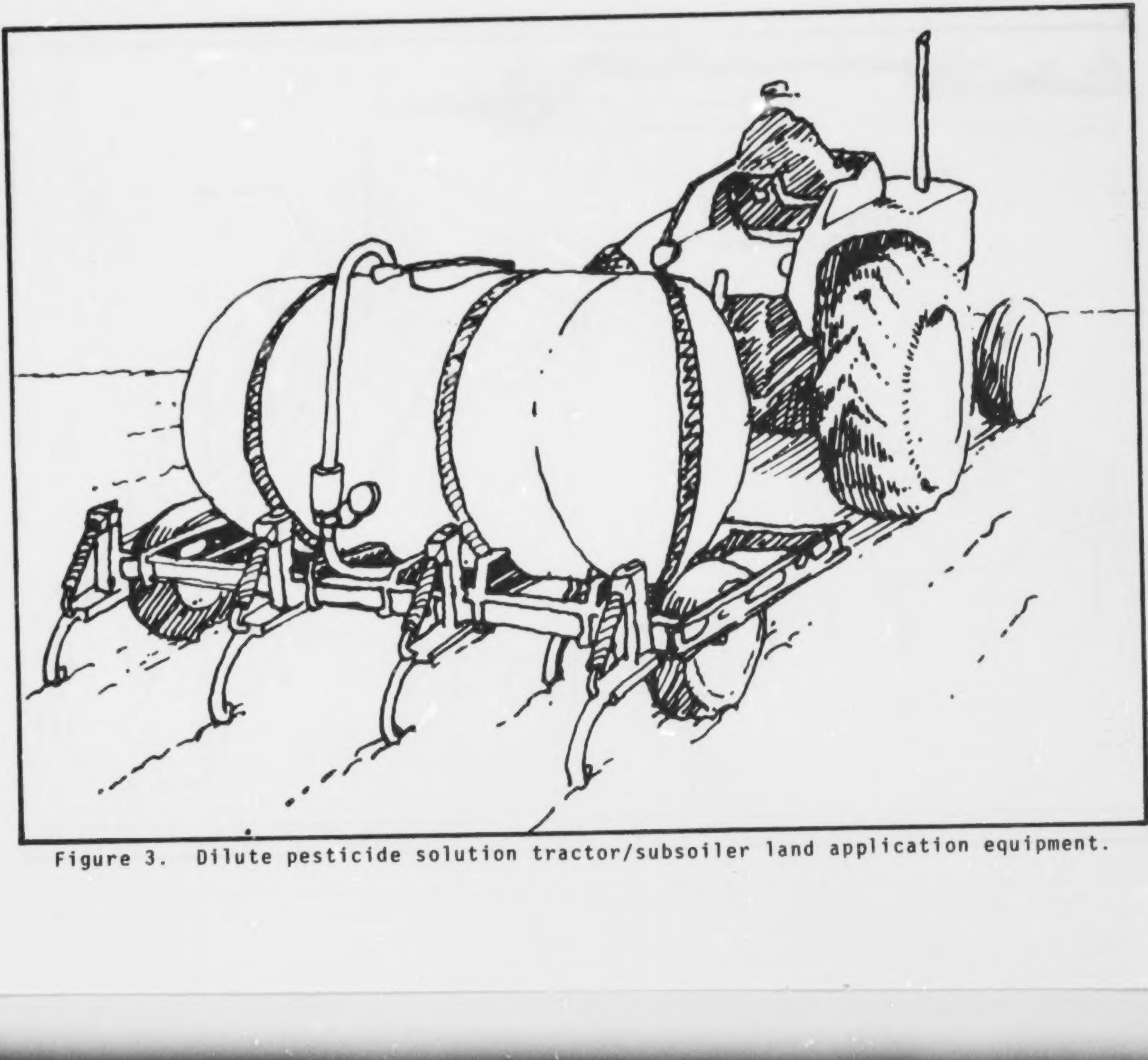

Figure 3. Dilute pesticide solution tractor/subsoiler land application equipment.

- The land is not perpetually dedicated to disposal, facilitating procurement of a disposal site.

Disadvantages include:

- Pesticide concentrations in the soil may exceed vegetation tolerance levels and prevent or inhibit plant growth.
- Plowing must cease during certain growth periods, leaving the pesticides on the soil and plant surfaces.
- The pesticide-contaminated vegetation may be unsafe for human or animal consumption and may itself present a disposal problem.

In general, the advantages of vegetation do not exceed the disadvantages sufficiently to recommend it as a routine practice. Specific tests and evaluations would need to be performed at each potential land cultivation site to determine the safety of crop growth and use under the given conditions.

### Soil Mounds and Pits

Soil mounds and pits are lined soil systems of limited area which can accept higher rates of dilute pesticide solution application than land cultivation. With a proper liner, pesticide migration is prevented. The pesticides can be allowed to accumulate in the system, although this entails periodic replacement of the soil.

There are two basic configurations of soil mounds and pits as depicted in Figures 4 and 5. Figure 4 depicts the type currently being used and evaluated for dilute pesticide solutions by the University of California. It consists of an excavated pit, lined with an impermeable membrane (butyl rubber) and backfilled with soil mounded above grade. A distribution box and series of small leach lines are used to distribute the dilute pesticide solutions throughout the system. The soil pit in Figure 5 is being evaluated by Iowa State University. It is a concrete-lined pit filled with soil and gravel. Wastewaters are sprayed onto the pit soil surface and allowed to percolate downward naturally into the pit.

Since research on soil mounds and pits is still not complete, little data are available to assess their true potential. They do have certain inherent advantages over land cultivation:

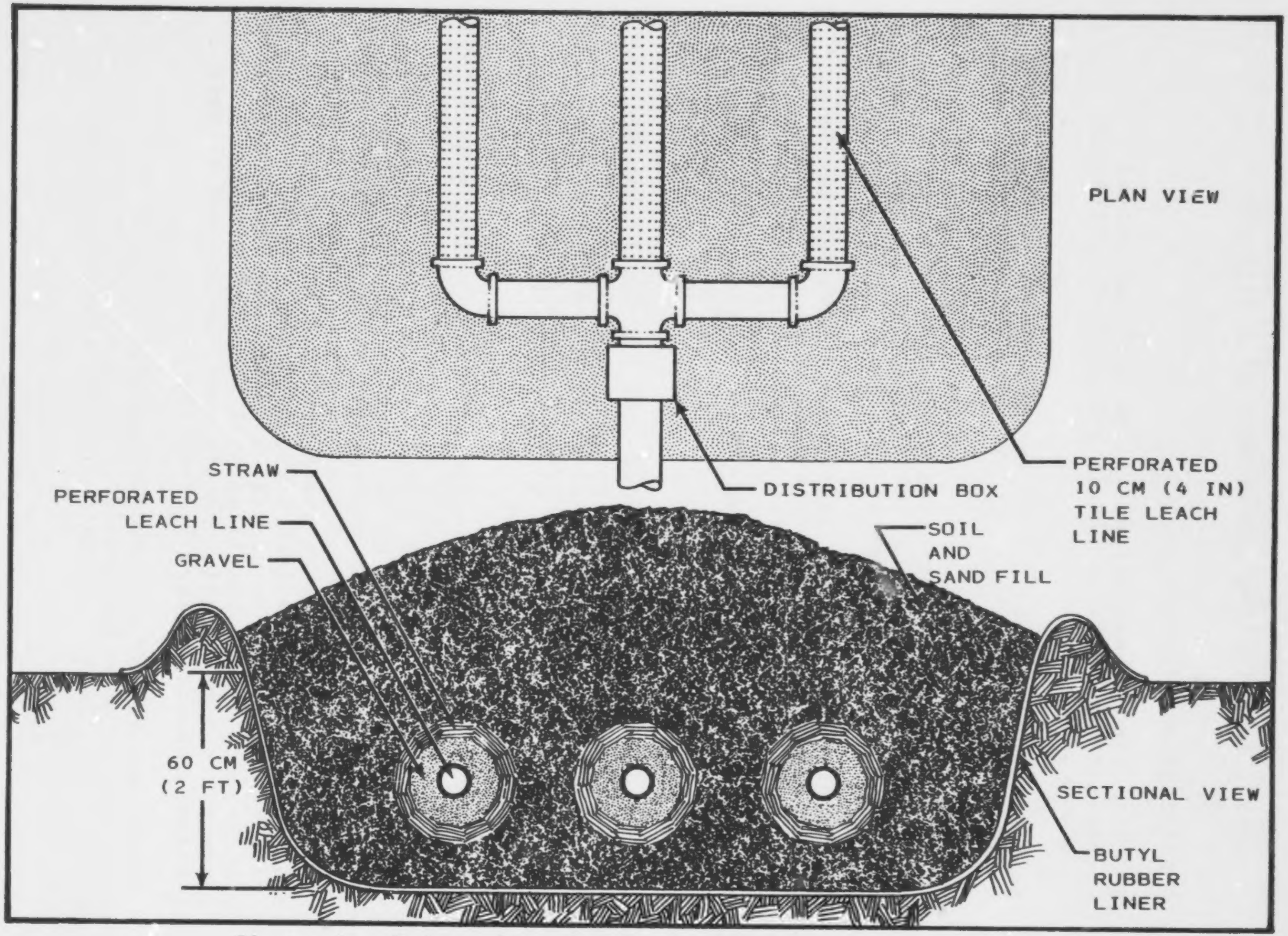
PLAN VIEW
PERFORATED 10 CM (4 IN) TILE LEACH LINE
DISTRIBUTION BOX
STRAW
PERFORATED LEACH LINE
GRAVEL
SOIL AND SAND FILL
60 CM (2 FT)
SECTIONAL VIEW
BUTYL RUBBER LINER

Figure 4. University of California soil mound system.

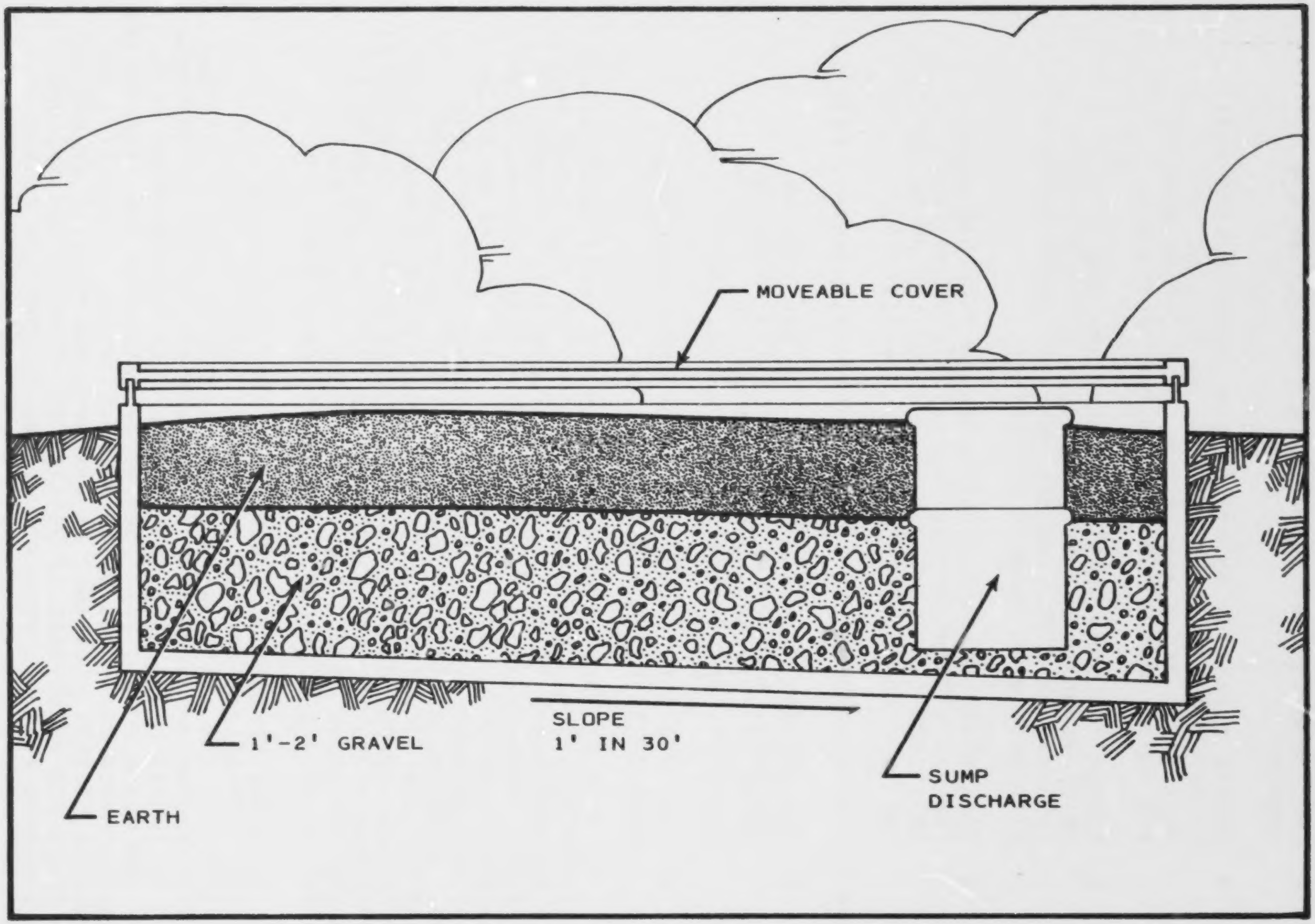
MOVEABLE COVER
EARTH
1'-2' GRAVEL
SLOPE
1' IN 30'
SUMP
DISCHARGE

Figure 5. Iowa State University soil pit disposal system.

- Less land is required because the systems are smaller.
- Dilute pesticide solutions are injected into soil mounds beneath the surface so no plowing is necessary, and a vegetative cover can be used to aid water loss through evapotranspiration.
- Except for some volatilization (the extent of which is unknown) the pesticides are contained entirely on site, and the possibility of contact with people or animals is minimal.
- Soil mounds can be constructed in suburban areas for use with urban applicator dilute pesticide solutions (at least one soil mound system is in use in suburban Orange County, California).

There are also some potential disadvantages, however, such as:

- The systems have a definite, limited life expectancy, unknown at this point but estimated at 10 yr (Personal communication, Mr. Richard Yamaichi, University of California, Davis).
- They are more expensive to construct than simple land cultivation systems.

The size of the system depends on the quantity of dilute pesticide solutions generated. Estimates of void space in a soil mound/pit are 10 to 15 percent of the total volume (Personal Communication, Mr. Richard Yamaichi, University of California, Davis). Application rates are limited by local evapotranspiration rates. When application rates are too high, or during periods of high rainfall, the system can flood and overflow (Figure 6). Consequently, any means used to increase evapotranspiration (vegetative covers, transparent roofs) can allow increased application rates or design of a reduced system of size. A typical system might be 6 m (20 ft) by 12 m (40 ft) by 0.9 m (3 ft) deep (48).

Once the system is constructed, only monitoring and routine maintenance on feed systems is normally needed. Periodically the system will become saturated with pesticides or degradation products so that further adsorption or degradation is impossible. When this occurs, the contaminated soil from the mound or pit will need to be excavated and transported to an approved hazardous waste disposal site. Presently, the frequency of this clean-out is unknown, but it will depend on the types and quantities of pesticides added to the system. The presence of a concrete pit or mound liner can reduce

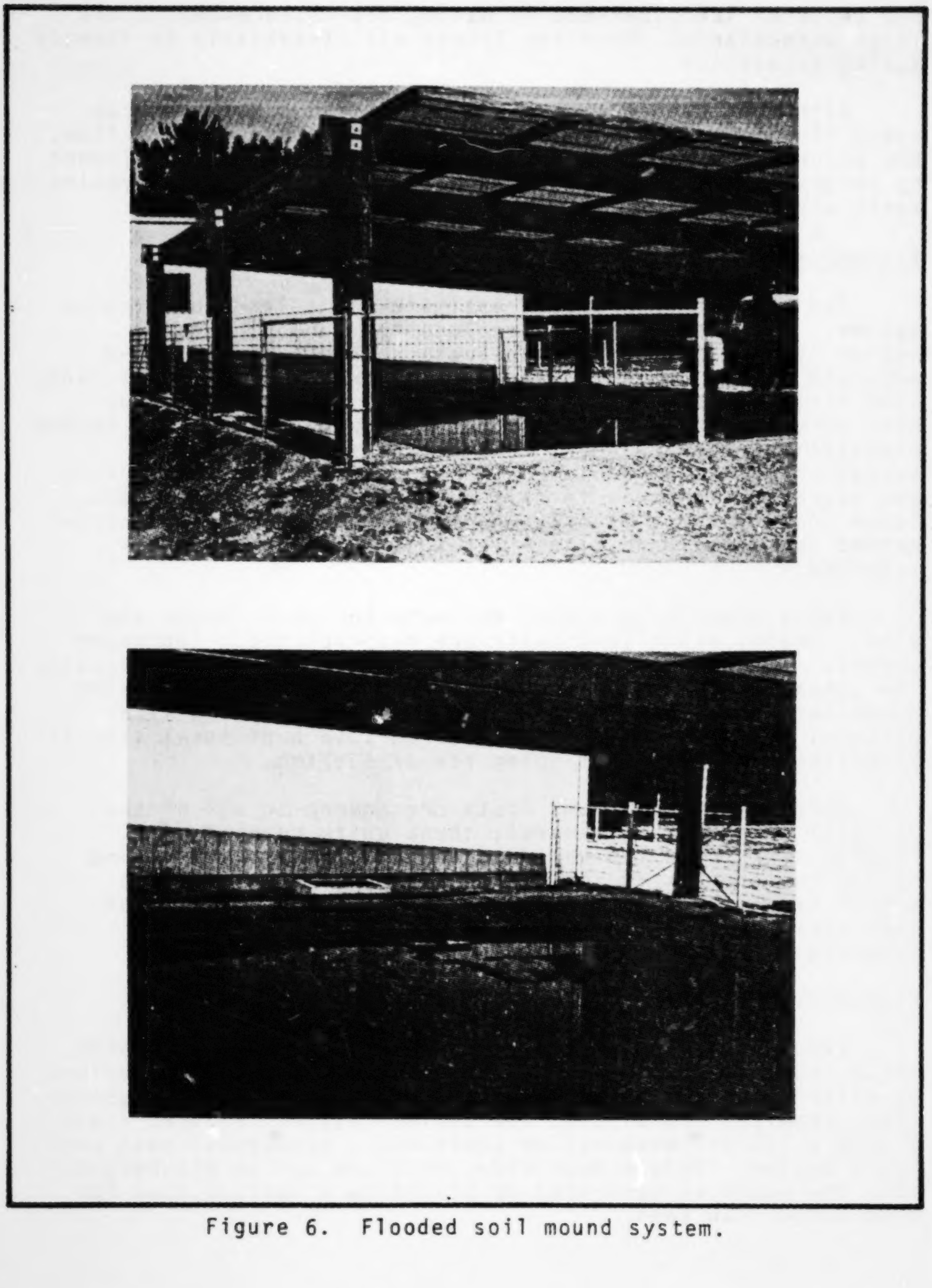

Figure 6. Flooded soil mound system.

the costs of the clean-out by making the replacement of the liner unnecessary. Membrane liners will inevitably be damaged during excavation.

Although more expensive to install and operate, a constant flow pump type feed system is better than gravity flow, the potential surge problems in a gravity feed system flooded by rainfall are avoided. Personnel and operator time requirements are minimal.

## Economics

Table 7 presents a cost estimate for a land cultivation system. These costs do not include the land, the major system component. If the applicator can use airport land adjacent to the runways or any nearby unused or marginal land, land costs can be held to a lease fee. If the applicator must purchase land, the costs of land cultivation could become prohibitive. Otherwise, the major cost element is the spreading/injection equipment. Labor costs include benefits and overhead. (Note: in this and all subsequent sections, labor costs reflect 1) only the hours devoted to the disposal method operation, and 2) the level of skill or training required.)

Table 8 presents a cost estimate for soil mounds and pits. Again, basic land costs are not included. The major expense is the initial construction of the mound or pit system. The annual operating cost estimate includes periodic system clean-out and disposal prorated over a 10-yr system life. Disposal costs assume a 30 mi transport to a disposal site at $0.2/ton-mi and a site tipping fee of $35/ton.

Holding tank and pump costs are common to all of the disposal methods. In general, these units consist of a holding tank below the wash/rinse area and the pump/piping needed to transfer the dilute pesticide solutions to the actual treatment system. Cost estimates include costs of laboratory services for monitoring and labor needed for sampling.

## EVAPORATION BASINS

Evaporation basins are open or covered basins or ponds which reduce the volume of applied dilute pesticide solutions by solar evaporation and treat the mass by microbial degradation, chemical hydrolysis, and sedimentation. Figures 7 and 8 show a typical evaporation basin and a conceptual wash pad/basin system. Dilute pesticide solutions can be discharged into the basin as generated or placed in a holding tank for controlled flow feed.

## TABLE 7. LAND CULTIVATION COST ESTIMATE*

Basis for calculations

1.7 $m^3$ (450 gal)/day
385 $m^3$ (102,000 gal)/yr
225 operating days/yr
1 hectare (2.47 ac) site

Capital Costs

| | |
|---|---|
| Holding tank (2,000 gal galvanized steel, underground, installed) | $ 1,750 |
| Pump | 600 |
| Tractor/subsoiler/nurse tank/pump assembly | 15,500 |
| Collection ditch and berm (9.85/m) | 3,940 |
| Runoff sump (lined) | 2,500 |
| Fencing | 700 |
| Total | $24,990 |

Yearly Operating Costs

| | |
|---|---|
| Monitoring | $ 2,400 |
| Electricity | 100 |
| Fuel, oil | 100 |
| Labor (175 hr @ $9.20/hr) | 1,610 |
| Maintenance | 700 |
| Fixed charges (25% of capital costs) | 6,247 |
| Total | $11,157 |

Operating costs per $m^3$ - $28.98
per gal - $ 0.11

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* Material, equipment, and operating costs based on Means Building Construction Cost Data 1978.

## TABLE 8. SOIL MOUNDS AND PITS COST ESTIMATES*

**Basis for Calculations**

1.7 $m^3$ (450 gal)/day
385 $m^3$ (102,000 gal)/yr
225 operating days/yr

| Capital Costs | Soil Mound | Soil Pit |
|---|---|---|
| Holding tank | $ 1,750 | $ 1,750 |
| Pump | 600 | 600 |
| Distribution box | 50 | -- |
| Pit, concrete liner, backfill (6m x 12m x 1m) | 7,500 | 7,500 |
| Leach lines | 450 | -- |
| Gravel, soil | 50 | 50 |
| Roof | 1,750 | 1,750 |
| Fencing | 700 | 700 |
| Total | $12,850 | $12,350 |

| Yearly Operating Costs | Soil Mound | Soil Pit |
|---|---|---|
| Monitoring | $ 2,400 | $ 2,400 |
| Electricity | 100 | 100 |
| Labor (250 hr @ $11/hr) | 2,750 | 2,750 |
| Fixed charges (25% of capital costs) | 3,212 | 3,087 |
| System clean-up and spent soil disposal (prorated over 10 yr) | 1,240 | 1,240 |
| Total | $ 9,702 | $ 9,577 |
| Operating costs per $m^3$ - | $ 25.20 | $ 24.88 |
| per gal - | $ 0.095 | $ 0.09 |

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* Based on Means Building Construction Cost Data 1978.

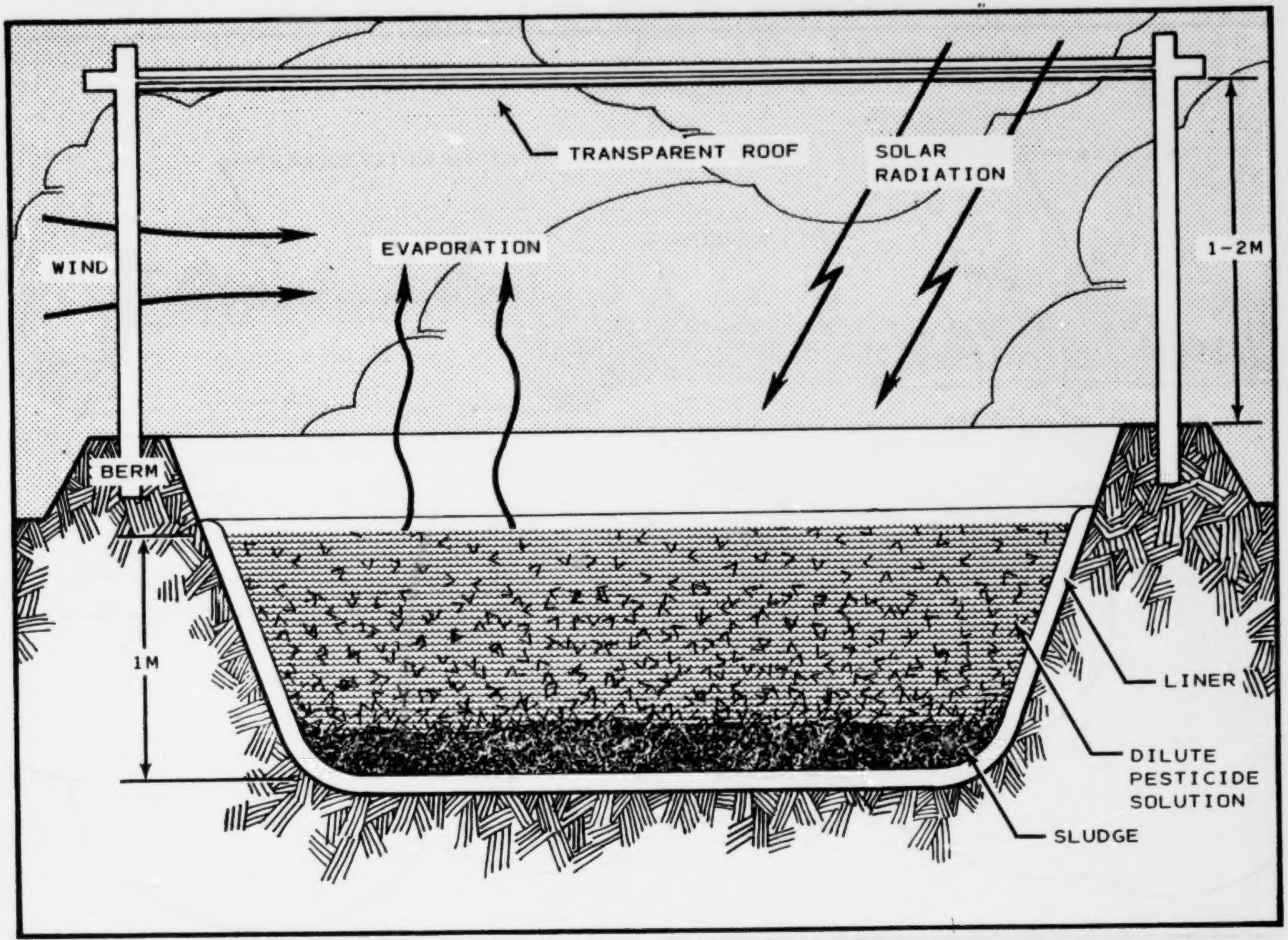
TRANSPARENT ROOF
SOLAR RADIATION
WIND
EVAPORATION
1-2M
BERM
1M
LINER
DILUTE PESTICIDE SOLUTION
SLUDGE

Figure 7. Evaporation basin.

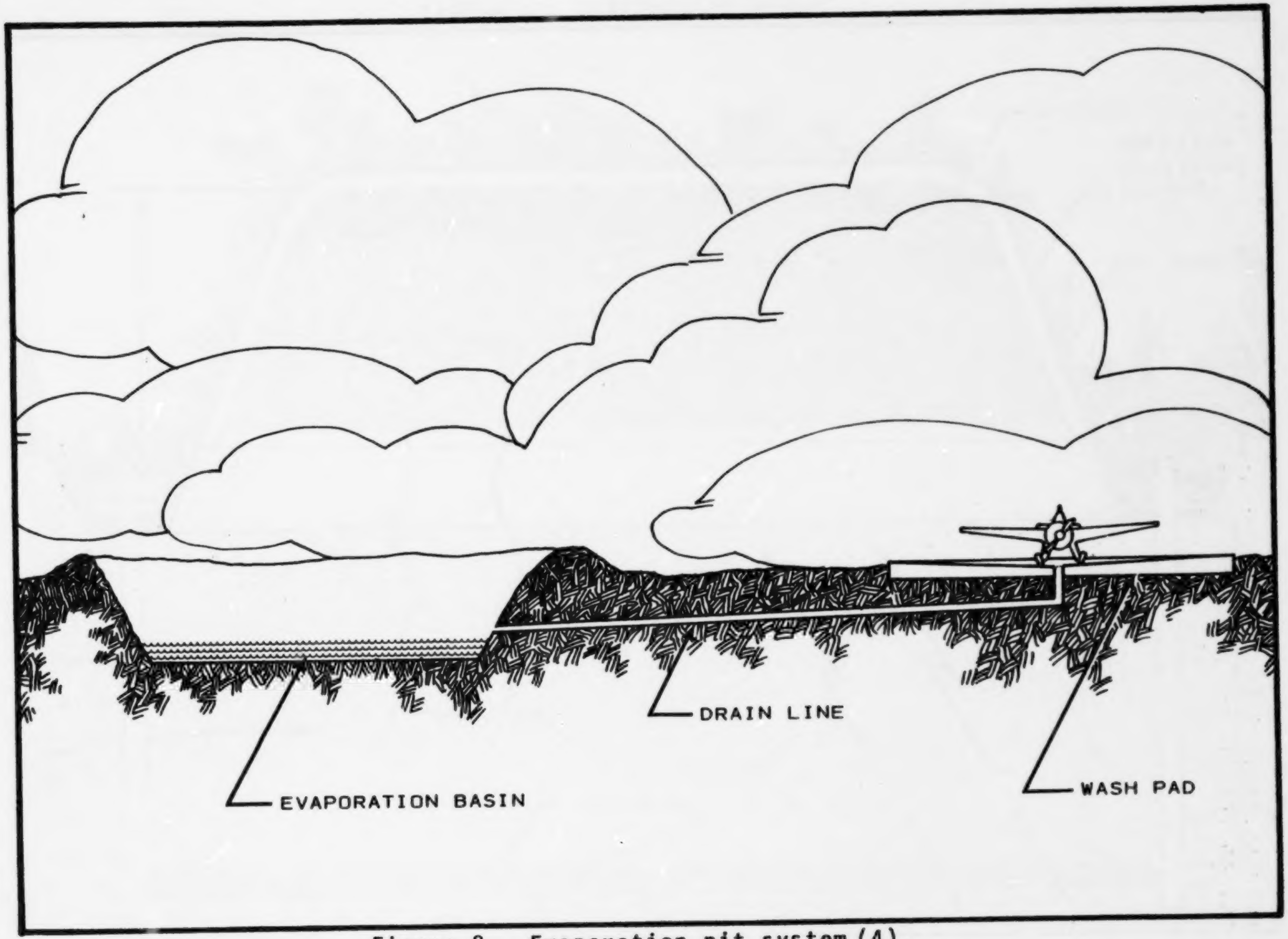
DRAIN LINE
EVAPORATION BASIN
WASH PAD

Figure 8. Evaporation pit system (4).

Evaporation basins are a common industrial waste treatment system. Thus, there are general guidelines for their design and operation. The basins should be located close to pesticide storage and equipment washdown areas to reduce transport hazards and costs. There should be no effluent from a basin to surrounding soil or underlying groundwater. Facilities should have protective enclosures to keep wildlife, domestic animals, and unauthorized persons out. Facilities should be protected from storms and flood water to ensure that erosion or other storm damage does not render any portion inoperable. Any sludges, pesticide residues, or contaminated soils taken from evaporation basins during cleanings must be disposed of in approved hazardous waste disposal sites. A basin must be lined to prevent any downward or lateral movement of pesticides beyond the disposal site confines to eliminate subsequent contamination of ground or surface water supplies. Soil or membrane liners may be effective, depending on pesticide type, liner material, and placement design. A combination concrete-over-membrane liner is most secure and least liable to mechanical damage.

As with land disposal, various mechanisms reduce the volume and treat the dilute solutions applied to evaporation basins. The primary mechanism to reduce the overall volume of the dilute pesticide solution is evaporation. As noted in the introduction, it is the large volume of waste that makes dilute pesticide solutions a critical hazardous waste disposal problem. Evaporation basins work to keep this volume low and steady and, thus, more manageable.

Note that evaporation of water tends to concentrate the pesticides remaining in the basin so the wastes and basin media may be hazardous. However, there are several mechanisms at work in the system that degrade or otherwise decrease pesticide concentrations.

Pesticides, even with low vapor pressures, will evaporate from open water (49-50). Thus, there is usually a distinct pesticide odor associated with evaporation basins used for concentrated wastes (48). It has been estimated that aldrin and DDT have evaporative half-lives (the time required for 50 percent of the compound to evaporate) in clean water of 7.7 and 3.0 days, respectively (49). However, little data are available on volatilization losses from water surfaces and no attempts have been made to obtain actual vapor loss rates. Estimates of vapor losses can be made based on thermodynamic considerations using data for Henry's constant (ratio of vapor concentration to solution concentration and usually taken as the ratio of the vapor pressure of the pure compound to the solubility in water of the pure compound) and assuming that atmospheric transport away from the water surface is limiting vapor loss. There has been little research on pesticide evaporation from dilute pesticide solution evaporation basins. Whether or not evaporation is a significant transport method depends on whether evaporation rates exceed adsorption or degradation rates. The presence of bottom muds or clays in the basin can greatly reduce pesticide evaporation through adsorption (24). Laboratory evaluation studies do not account for the competing degradation mechanisms (e.g. photolysis, hydrolysis) which also act on the pesticides.

Photolysis of pesticides can be significant in any open water system (51-54). However, ultra-violet radiation will only penetrate a few millimeters into the water (53). Consequently, shallow basins have an advantage over deeper systems in regard to photolysis. Photolysis degradation rates measured in laboratory studies indicate half-lives in terms of a few hours for some pesticides (51). The presence of photosensitizers can greatly enhance photolysis (51, 54). Photosensitizers (e.g., humic acids) facilitate the transfer of light energy into the pesticides, thus increasing the reaction rate.

Chemical hydrolysis can also be an effective degradation mechanism in evaporation basins (13, 51). Hydrolysis rates can also vary, depending on other substances in the water. Hydrolysis seems to be faster when the pesticides are adsorbed onto clay or silt particles, suggesting it may be adsorption catalyzed (13). The pH of the water can also significantly influence degradation. Research with malathion has demonstrated hydrolysis half-lives in neutral water and at pH 9 of one month and ten hours, respectively (51). Many industrial pesticide waste evaporation basins are kept alkaline to enhance degradation (55). Alkaline hydrolysis is not effective with every pesticide but has been shown to work with organophosphates, carbamates, imides, and hydrazides (55).

Microbial degradation can also play a role in reducing pesticide concentrations in evaporation basins, although probably not as great as the other mechanisms. To be truly effective, microorganisms require a near neutral pH and a low humic acid content (51). Under these conditions, chemical hydrolysis and photolysis are minimized, because hydrolysis generally proceeds better under alkaline conditions, and humic acids are photosensitizers. Research is needed to determine which approach is most effective in reducing pesticide levels in evaporation basins, particularly in basins that receive dilute solutions.

The major limitation to evaporation basin operation is the evaporation-precipitation gradient (4). For the system to work, evaporation rates must exceed precipitation rates. In areas of high rainfall, a transparent or semi-transparent roof is needed to keep out rainfall although roofing may result in slight decreases in evaporation (4, 55).

A basic consideration in designing an evaporation basin is to ensure that the volume of incoming solution is less than or equal to the volume of water leaving the basin via evaporation, as expressed below (4):

$$Qw + Op \leq Qe \tag{3}$$

where:

$Qw$ = volume of pesticide wastes ($ft^3$)

$Qp$ = volume of precipitation

$Qe$ = volume of evaporation.

These parameters can be estimated as follows:

$$Qw = \frac{nWD_o}{7.48} \quad (Qw \text{ in } ft^3) \tag{4}$$

where:

$n$ = no. of vehicles to be washed

$W$ = amount of washwater/vehicle, gal

$D_o$ = no. of operating days

$$Qp = \frac{q_p A_t D}{4,380} \tag{5}$$

where:

$q_p$ = annual average precipitation, in/yr

$A_t$ = top area of basin, $ft^2$

$D$ = elapsed no. of days (usually 365)

$$Qe = \frac{q_e A_f D}{4,380} \tag{6}$$

where:

$q_e$ = annual average evaporation rate, in/yr

$A_f$ = surface area of fluid, ft$^2$.

Equation (3) can then be restated as follows:

$$\frac{nWD_o}{7.48} + \frac{q_p \ A_tD}{4,380} \leq \frac{q_eA_fD}{4,380} \qquad (7)$$

To obtain the proper area ($A_f$ in ft$^2$) for a vertical walled basin,

$$A_f = \frac{-1.6 \ nWD_o}{q_p - q_e} \qquad (D = 365 \text{ days}) \qquad (8)$$

(Note: if $q_p = q_e$, set $q_p - q_e - 1$. Also, $q_p$ and $q_e$ should be expressed as whole inches.) Since most basins have sloped sides, $A_f \neq A_t$. Furthermore, the top of the pit (t) should be at least 60 cm (2 ft) above the fluid surface (f) to contain a 10-yr, 24-hr storm and/or wind wave action. Consequently,

$$A_t = (\sqrt{A_f} + \frac{2H}{5})^2 \qquad (9)$$

where:

H = height of t above f

S = side slope of basin (use/run).

The area of the basin base (ft$^2$) is,

$$A_b = (\sqrt{A_f} - \frac{2d}{S})^2 \qquad (10)$$

where:

d = maximum depth of fluid (ft).

During evaporation, the surface area of the fluid will change with changing evaporation rates. Thus, the average fluid surface area must be calculated as follows:

$$A_{fa} = \frac{A_f \ (100\text{-}EV)(100)}{2} \qquad (11)$$

where:

EV = evaporation variance (%)

$$= \frac{A_f - A_b}{100\ A_f}$$

Substituting this in Equation 7 yields

$$\frac{nWD_o}{7.48} + \frac{q_p A_t D}{4,380} \leq \frac{q_e A_{fa} D}{4,380} \tag{12}$$

To compute the volume of fluid on hand in the basin at the end of the application season, set $D = D_o$ and solve. To calculate if this volume will be removed during the idle season, set the first term in Equation 7 equal to zero and substitute $D\text{-}D_o$ for D. If the net quantity of fluid removed is less than the amount on hand at the end of the season, a larger pit should be selected. A quickly converging iterative procedure will probably be needed to arrive at the proper size.

The volume contained below the computed fluid level should be determined as follows:

$$V\ (\text{in ft}^3) = 1/3\ d\ (A_f + \sqrt{A_f A_b} + A_b) \tag{13}$$

This basin volume should be greater than or equal to the waste volume on hand at the end of the application season.

For a roofed basin in a high precipitation area the same design equations can be used by setting $q_p$ equal to zero, or a very low number, to account for windblown incident precipitation, and solving as above.

Evaporation basins are most frequently used by pesticide formulating and packaging plants for their process wastewater and washwater (55). Industrial basins range from shallow concrete pads to earthen ponds lined with bentonite, plastic membranes, or other impermeable liners. Small ponds (less than about 2,500 ft$^2$) are usually roofed (55). Some systems add simple spray or waterfall aeration to increase evaporation. Occasionally supplemental heat from immersion heaters is applied.

Industrial experience has shown that evaporation basins are simple to construct and operate. Usually only one person is needed, and he must spend less than 10 percent of his time in monitoring the basin, adding chemicals, and maintaining the pumps (55). As noted above, most industrial basins are kept at about pH 9 to enhance hydrolysis.

## Advantages

Evaporation basins are simple systems that can be installed anywhere sufficient land is available. They require a minimum of operating personnel and time to ensure proper operation. Thus, the ease of operation is a major advantage.

## Disadvantages

Evaporation basins do not work efficiently in areas with low evaporation rates or long periods of freezing temperatures (4). Water evaporates (submlimes) very slowly from a frozen basin. Periods of freeze reduce the factor D in Equation 5. Thus, there are some climatological limitations.

The major potential disadvantage is the possible air quality impairment from pesticide volatilization. At this point the extent of the problem is unknown. Further research is needed to fully quantify the potential emissions.

## Economics

Table 9 presents a cost estimate for an evaporation basin. The major cost element is construction of the basin itself. Use of an appropriate plastic or bentonite liner instead of concrete could reduce costs. The aeration pump system is optional. If an applicator wishes to keep the water in the basin at pH 9, additional chemical costs of about $250/yr can be expected. The capital costs do not include land costs.

## Summary

Overall, the concept of land disposal has both advantages and disadvantages. Advantages include:

- Generally lower costs compared to other, more elaborate disposal methods
- Availability of appropriate equipment and personnel in rural agricultural areas
- Overall ease and simplicity of operation
- The demonstrated effectiveness of some soils in containing and degrading many pesticides.

## TABLE 9. EVAPORATION BASIN COST ESTIMATE*

Basis for Calculations

1.7 $m^3$ (450 gal)/day
385 $m^3$ (102,000 gal)/yr
225 operating days/yr

| | | |
|---|---|---|
| **Capital Costs** | | |
| Holding tank | | $ 1,750 |
| Pump | | 600 |
| Concrete lined basin (4.5 m x 9 m x 1 m) | | 3,500 |
| Aeration pump system | | 1,200 |
| Roof | | 1,750 |
| Fencing | | 700 |
| | Total | $ 9,500 |
| **Yearly Operating Costs** | | |
| Monitoring | | $ 2,400 |
| Electricity | | 100 |
| Labor (250 hr @ $11/hr) | | 2,750 |
| Fixed charges (25% of capital costs) | | 2,375 |
| System clean-out and sludge disposal | | 850 |
| | Total | $ 8,475 |

Operating costs per $m^3$ - $22.01
per gal - $ 0.08

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* Ferguson, T. L. Pollution control technology for pesticide formulators and packages, 1975, (55) updated to 1978 using standard engineering cost indices.

Disadvantages include:

- A lack of comprehensive data on the types and concentrations of pesticides that are amenable to land disposal
- The uncertainties surrounding the movement and degradation of many pesticides and degradation products is soil systems
- A lack of control over the ultimate fate of the pesticides, compounded by a relative inability to predict either causes or consequences (6).

The disadvantages are of more consequence in regard to land cultivation than soil mounds or pits. Even with a liner, the potentials for air and water contamination through leaching, runoff, and evaporation are much higher with land cultivation. Research has indicated that these transport phenomena are concentration-related (44). Consequently, there are circumstances under which land cultivation could be effective, but research to date has not clearly defined these circumstances.

The major problem of environmental safety and pesticide migration is largely eliminated with soil mounds and pits. With proper liner selection, there is little potential for subsurface migration. Roofs, berms, and sunken soil surfaces serve to prevent runoff. The only remaining potential transport pathway is evaporation and the significance of this route has not been fully evaluated.

## CHEMICAL TREATMENT

The objective of chemical treatment is to convert the toxic constituents of dilute pesticide solutions into harmless or less toxic forms. Under ideal conditions, the treated dilute pesticide solution would be amenable to safe disposal by any conventional wastewater disposal method without the precautions necessary for hazardous waste streams. Typical types of chemical treatment are oxidation, hydrolysis, and precipitation. Oxidation and hydrolysis act on the chemical structure of the pesticide, breaking the molecule down into smaller, more biodegradable fragments or removing various functional groups. Precipitation converts the pesticide into an insoluble form which can be removed as a sludge. This sludge must be treated as a hazardous waste, but the volume is considerably less than the original dilute pesticide solution.

Figure 9 shows a typical arrangement for a chemical treatment system. Equipment requirements consist primarily of a lined reactor (concrete, steel, or fiberglass tank; lined basin, pond, lagoon) with a stirring mechanism (mechanical, aerator) and chemical storage and feed equipment. To eliminate air emissions, a closed tank is advisable. Use of several different treatment chemicals might require several chemical feeders or thorough cleaning between treatments.

Maintenance would be limited to periodic servicing of mechanical feed and metering equipment and stirrers. In addition, occasional cleaning of pipelines, tanks, and reactors would be necessary. Aside from maintenance, routine operations would require one person to select, measure, and feed the treatment chemicals and monitor the treatment process. Chemical treatment could be conducted concurrently with other routine applicator operations.

No single chemical procedure exists for degrading the entire spectrum of pesticides (56). Some pesticides are not readily amenable to chemical treatment (Table 10). The more commonly used pesticides are considered to be susceptible to chemical treatment. In some cases, degradation products may be hazardous. For instance, dimethoate can be entirely degraded by alkaline hydrolysis. The degradation product, mercaptoacetic acid, is almost as toxic as the dimethoate (58). Moreover, the appropriate reagents may be exotic, expensive, or extremely hazardous, and the degradation process may require special equipment, conditions, or skills not readily available outside of research laboratories. While some pesticides can be completely degraded by chemical treatment (e.g. Def) slow reaction times make the method of questionable value (58). The applicability of chemical treatment must be evaluated in terms of the specific pesticides to be treated (57).

There has been considerable research on chemical treatment methods, particularly for the more concentrated solutions of industrial pesticide wastes and waste pesticides (56-62). Some of the results are applicable to dilute pesticide solution treatment. For instance, 2,4-D and 2,4,5-T react readily with hydrogen peroxide (56). Chlorine dioxide reacts with diquat and paraquat under alkaline conditions (56). Carbamates and organophosphorus pesticides are generally susceptible to hydrolysis (Table 11). Potassium permanganate reasily oxidizes parathion in alkaline media (63). Exhaustive chlorindation is not recommended for nitrogen, phosphorus, or organo-metallic pesticides because toxic by-products can form (18).

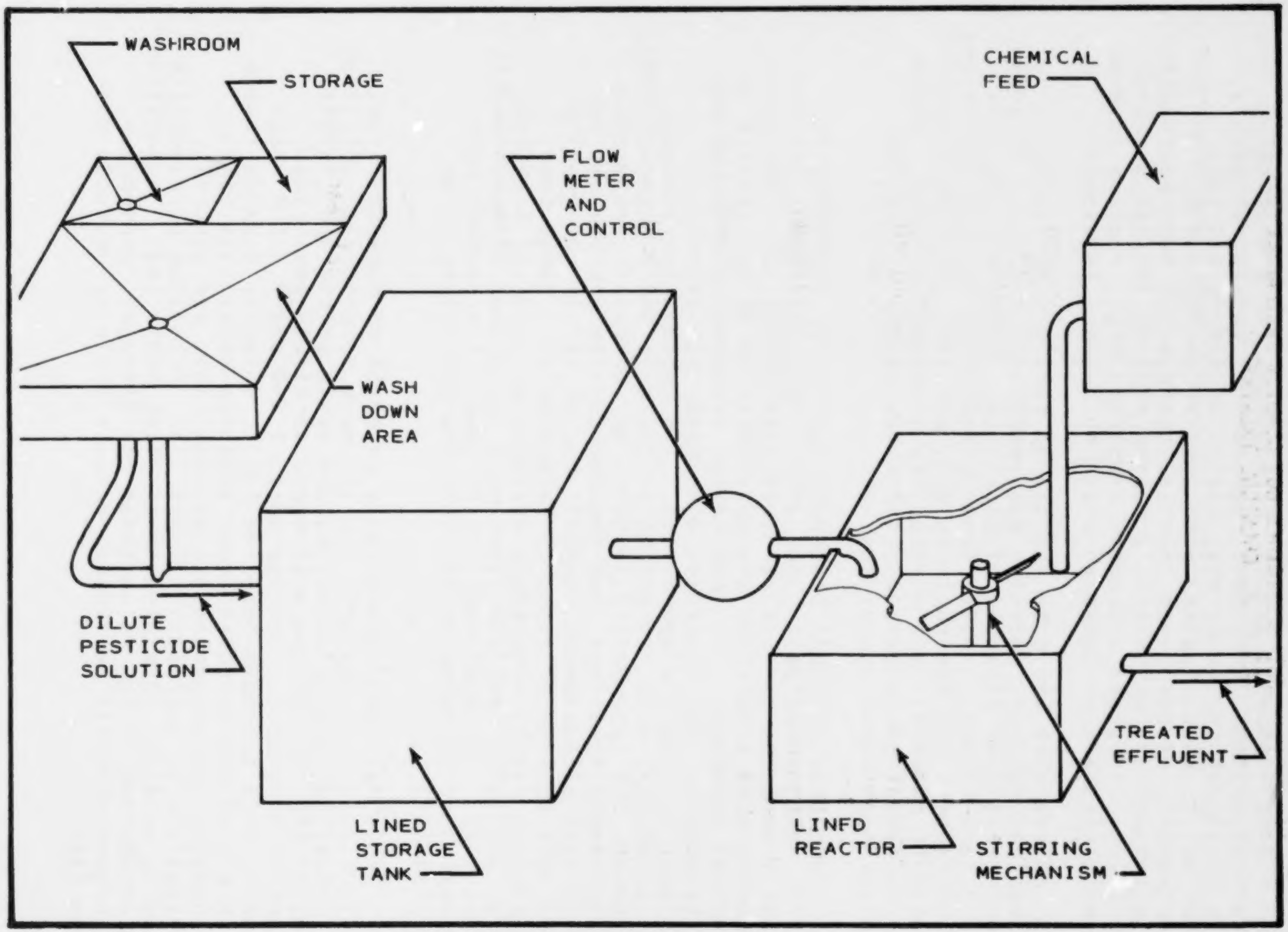
WASHROOM
STORAGE
FLOW METER AND CONTROL
CHEMICAL FEED
WASH DOWN AREA
DILUTE PESTICIDE SOLUTION
LINED STORAGE TANK
LINED REACTOR
STIRRING MECHANISM
TREATED EFFLUENT

Figure 9. Chemical treatment system.

## TABLE 10. SOME PESTICIDES NOT READILY DEGRADABLE BY PRACTICAL CHEMICAL TREATMENT*

Dursban
Methyl Parathion
Maneb
Alachlor (Lasso)
Diuron
Picloram
Trifluralin
Methoxychlor
Chlordane
Toxaphene
Amiben
Pentachlorophenol
Ronnel
Dimethoate
Dyfonate
Def
EPTC
Molinate
Thiram
Propanil
Diphenamid
Chloroxuron
Cyanazine
Simazine
Amitrole
PCNB
Dinoseb
Chloropicrin
Chlorobenzilate
Endrin
D-D
BHC (Lindane)
DBCP
Dicamba
Sodium Fluoroacetate
Creosote
Warfarin
Arsenic Acid
MSMA

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* Shih and Dal Porto. Handbook of pesticide disposal by common chemical methods, 1975 (57).

Lande, S. S. Identification and description of chemical deactivation/detoxification methods for the safe disposal of selected pesticides, 1978 (58).

TABLE 11. SELECTED PESTICIDES AMENABLE TO ALKALINE HYDROLYSIS*

| Pesticide | Alkalinity | Half-Life |
|---|---|---|
| Parathion | 1N NaOH | 32 min |
| Methyl parathion | 1N NaOH | 7.5 min |
| Malathion | pH 10.03 | 28 min |
| DDVP | pH 8.0 | 462 min |
| Diazinon | pH 10.4 | 144 hr |
| Carbaryl | Alkaline | Rapid |
| Propoxur | pH 10.0 | 40 min |
| Phosphamidon | pH 10 | 2.2 days |

* Dennis, W. H., Jr. Methods of chemical degradation of pesticides and herbicides, 1972 (56).

Shih and Dal Porto. Handbook of pesticide disposal by common chemical methods, 1975 (57).

On the other hand, much of the research has used exotic, rare, or hazardous treatment chemicals which would not be practical for dilute pesticide solution treatment in the field. Examples of these include liquid ammonia with sodium metals, chromous chloride in acetone, t-butyl alcohol and lithium metal in tetrahydrofuran, and lithium iodide in boiling collidine (56, 59). In general, for a chemical treatment method to be acceptable for dilute solutions encountered by applicators and farmers, the reagents and solvents should:

- Be relatively common
- Be low in cost
- Produce no fire hazard
- Be non-toxic to fish and mammals under normal use conditions
- Produce degradation products that are safe to handle and can be disposed of in non-hazardous waste facilities (56).

### Advantages

Chemical treatment is reliable and results are reasonably predictable (62). Under ideal circumstances, an innocuous waste stream can be produced. Chemical treatment is largely independent of climatic or geographical limitations. Treatment systems can be set up almost anywhere and seldom require much land area. Well-designed systems will not result in stray water or air emissions. Chemical treatment is one of the few systems which can be adapted for use by urban pesticide applicators.

### Disadvantages

Chemical treatment systems often do not yield complete detoxification because (1) insufficient time is allowed or (2) insufficient treatment chemical is used. Even when complete degradation is readily achievable, the reaction product may be as hazardous as the pesticide, as is the case with dimethoate (58). Consequently, the effluent from a chemical treatment system may be far from innocuous.

If an applicator uses a variety of pesticides, many different treatment chemicals might be necessary, raising problems of both original cost and storage. For instance, fensulfothion is amenable to alkaline hydrolysis but chemical oxidation forms toxic end-products. On the other hand, paraquat is not amenable to alkaline hydrolysis but is readily susceptible to oxidation with chlorine or permanganate. Moreover, most treatment chemicals are themselves hazardous and require special handling, although usually within the abilities of the applicator.

Determination of the proper stoichiometric amount of treatment chemicals requires analysis of the dilute pesticide solution and a knowledge of the treatment chemistry (or a producer-supplied table of precise amounts). The amount could be estimated based on formulation rates, but this would generally lead to an excess of treatment chemical. If too little treatment chemical is added, incomplete detoxification will result; too much chemical and a new waste chemical solution could be created. If an unskilled operator uses the wrong combination of chemicals (e.g. sodium sulfide plus hydrochloric acid), toxic gaseous by-products (e.g. hydrogen sulfide) could be produced. A dilute pesticide solution containing several different pesticides might require sequential treatment by different methods or reagents. In any case, knowledge of the constituents and concentrations in the dilute pesticide solution are mandatory before treatment, requiring on-site analytical facilities and appropriate personnel.

### Economics

Table 12 presents a cost estimate for chemical treatment. Major expenses are for treatment equipment and operations. Chemical costs can vary widely depending on the types and concentrations of pesticides in the dilute pesticide solutions. For this estimate, costs are based on alkaline hydrolysis with sodium hydroxide. Land costs are not included. Labor costs reflect the increased skills and time required to operate and maintain chemical treatment systems.

## PHYSICAL TREATMENT

Physical treatment processes rely on solute-solvent interactions and the physical properties of solutes and solvents to effect pesticide removal. Their primary functions are separation of liquid and solid phases and concentration, removal, or recovery of dissolved contaminants. Among the physical treatment processes that have been considered for dilute pesticide solutions are adsorption, reverse osmosis, distillation, electrodialysis, and liquid-liquid extraction.

Most of these processes have limited potential for treating dilute pesticide solutions, except as they might be used as an integral step in a more complex waste treatment system. Some have been used only in experimental or pilot operations.

## TABLE 12. CHEMICAL TREATMENT COST ESTIMATE*

Basis for Calculations

1.7 $m^3$ (450 gal)/day
385 $m^3$ (102,000 gal)/yr
225 operating days/yr

| Capital Costs | | |
|---|---|---|
| Holding tank | | $ 1,750 |
| Pump | | 600 |
| Reaction tank (4,000 gal capacity, lined) | | 3,000 |
| Chemical feeding and mixing equipment | | 2,500 |
| Fencing | | 700 |
| | Total | $ 8,550 |

| Yearly Operating Costs | | |
|---|---|---|
| Monitoring | | $ 600 |
| Electricity | | 300 |
| Treatment chemicals | | 2,000 |
| Labor (400 hr @ $12/hr) | | 4,800 |
| Fixed charges (25% of capital costs) | | 2,137 |
| Maintenance | | 1,000 |
| Waste disposal | | 2,500 |
| | Total | $13,337 |

Operating costs per $m^3$ - $34.64
per gal - $ 0.13

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* Equipment, material, and operating costs are based on Means Building Construction Cost Data 1978. Chemical costs are from chemical supply catalogs.

Most require highly specialized equipment and training. Given the current state-of-the-art, only reverse osmosis and adsorption show promise as dilute pesticide solution treatment methods.

## Reverse Osmosis

Most advanced applications of reverse osmosis (R. O.) are for desalination of brackish water. As a small-scale pesticide wastewater treatment method, R. O. is still in the experimental stage. In recent years, there has been considerable work on the development of small R. O. systems for treating agricultural wastewaters (64). Research with pesticides has shown R. O. to be very effective (99.5 percent) in removing nonpolar pesticides from solutions at concentrations ranging from 0.25 to 3 ppm (65). Conversely, R. O. has not been as effective in removing polar pesticides and low molecular weight organic compounds in general (66). Membrane deterioration and fouling continue to be problems. Consequently, several studies, while recognizing its potential value, have relegated R. O. to a secondary position at present (6, 66, 73). Therefore, R. O. will not be discussed in any further detail.

## Adsorption

Adsorption on activated carbon, adsorbent clay, and other natural and synthetic adsorbents is an effective means of removing many organic substances from dilute aqueous solutions. It is widely used in water and wastewater treatment for the removal of trace organics and taste- and odor-causing substances. Some pesticide manufacturing plants use activated carbon on an experimental basis or as a waste pretreatment or final polish method (54). There have been numerous studies on the use of adsorption for removing pesticides from water, and the results are generally good (65). One study used activated carbon to treat container rinsate (approximately 500 ppm) and achieved 98 percent removal (6). The use of pine bark dust instead of carbon was found to reduce concentrations of Sevin from 500 to 1 ppm at bark dust dose rates of 3 kg/3.8 $m^3$ (6.6 lb/1,000 gal) (6).

Adsorption units are available in either bed or column configurations. In general, column units (Figures 10 and 11) would be most appropriate for treating dilute pesticide solutions. Portable units are available for seasonal users (e.g., summer camps or resorts). In addition to the column itself and the various pumping and metering equipment, monitoring equipment and a source of make-up sorbent are needed. Monitoring equipment will identify the breakthrough point when the adsorbent has become saturated and must be replaced.

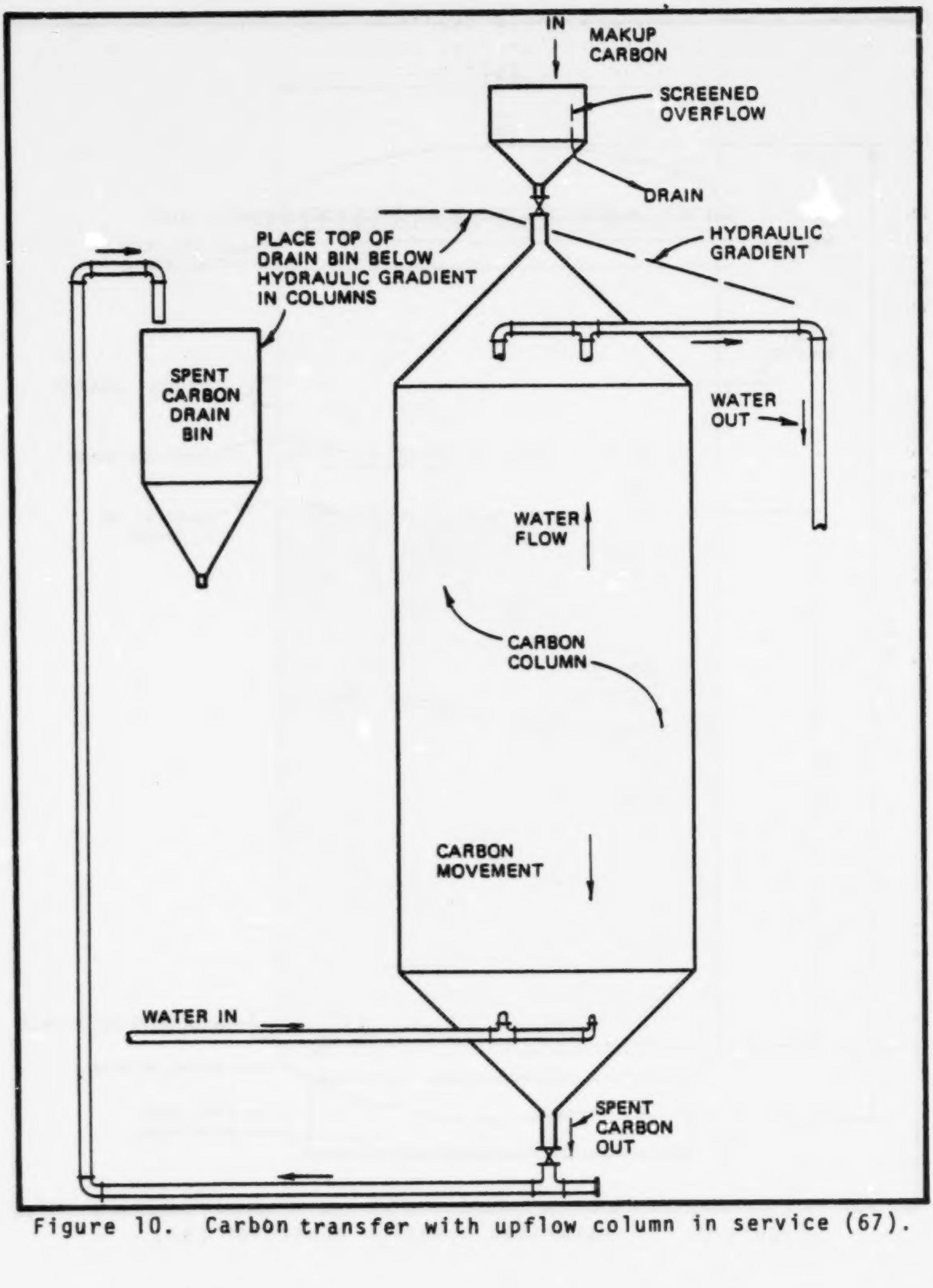
IN
MAKUP CARBON
SCREENED OVERFLOW
DRAIN
PLACE TOP OF DRAIN BIN BELOW HYDRAULIC GRADIENT IN COLUMNS
HYDRAULIC GRADIENT
SPENT CARBON DRAIN BIN
WATER OUT
WATER FLOW
CARBON COLUMN
CARBON MOVEMENT
WATER IN
SPENT CARBON OUT

Figure 10. Carbon transfer with upflow column in service (67).

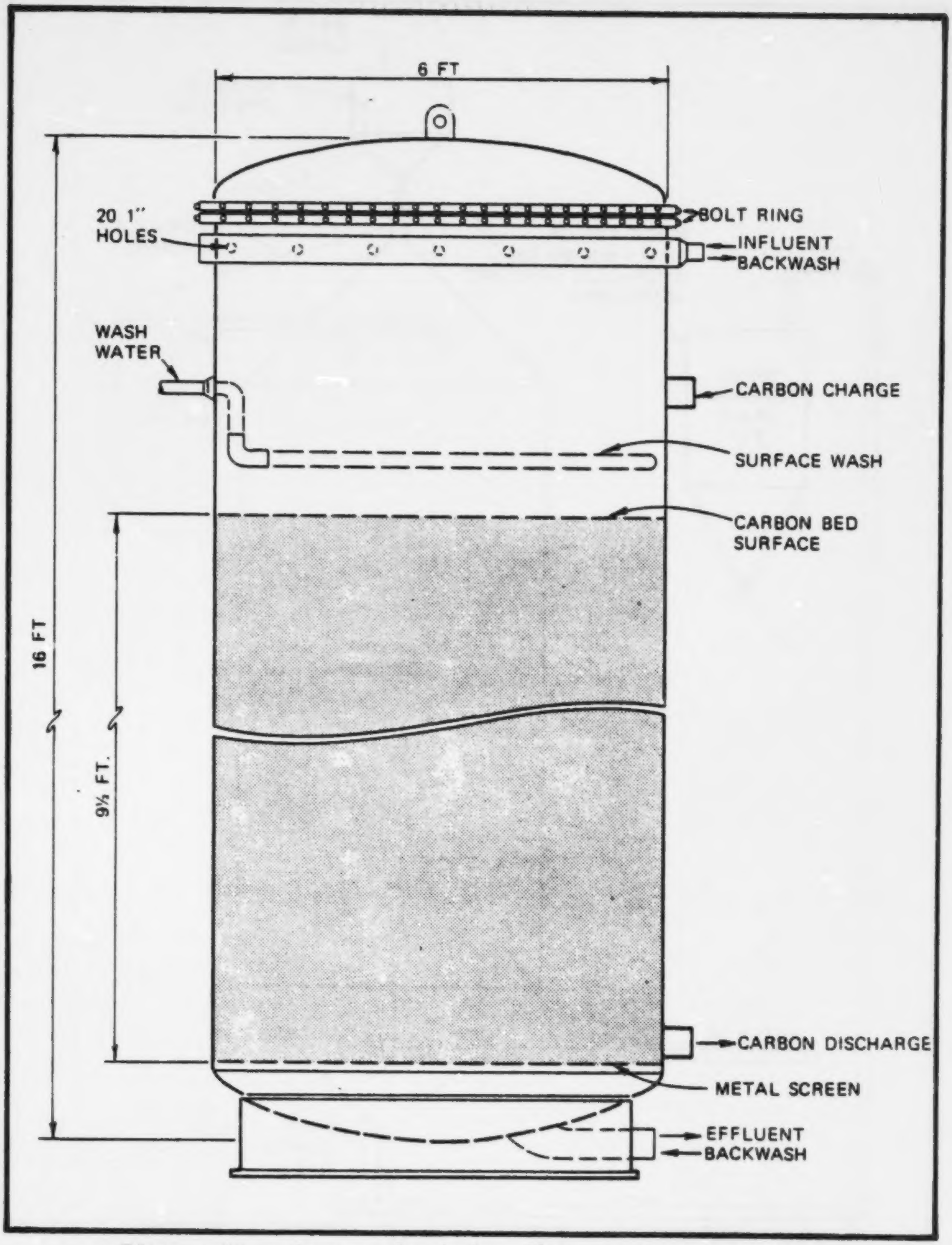
6 FT
20 1" HOLES
BOLT RING
INFLUENT
BACKWASH
WASH WATER
CARBON CHARGE
SURFACE WASH
CARBON BED SURFACE
16 FT
9½ FT.
CARBON DISCHARGE
METAL SCREEN
EFFLUENT
BACKWASH

Figure 11. Pressurized downflow contactor (67).

It would be impractical for the pesticide applicator to regenerate spent adsorbent, so new adsorbent would be needed regularly if such a process were used to treat a dilute pesticide solution stream.

## Advantages

Adsorption units are available in almost any size for any application. They can be installed almost anywhere and, with proper insulation, are not subject to geographical or climatological limitations. Removal efficiencies of 98 percent and better have been attained. Little specialized training is required to operate a simple adsorption unit, although some types of adsorption devices demand extensive training. Maintenance, particularly of monitoring devices, can be a special problem. Since adsorption units are closed systems, opportunities for spills, volatilization, public harm, or damage to wildlife, stock, or crops are minimal. Adsorption units could conceivably be adapted for use by urban pesticide applicators.

## Disadvantages

A disadvantage to adsorption, and, in reality, all physical treatment processes, is that the pesticides are not destroyed. In adsorption, this is partially overcome by the fact that the waste is changed from a large volume, dilute liquid waste to a small volume, concentrated solid waste. This greatly simplifies the original hazardous waste disposal problem. The volume of wastes will be less, but the concentration will be greater. For instance, adsorption generates a solid waste with a high pesticide content; reverse osmosis generates a highly concentrated wastewater. It is imperative to treat these wastes with a highly efficient destructive treatment method or transport them to an appropriate hazardous waste disposal site, but in either case, the costs and problems are less than with the original wastewater.

Many pesticide formulations contain inert carriers (e.g., clay), other insoluble inorganic ingredients (e.g., sulfur), insoluble pesticide powders or granules, or oil carriers (9, 47, 68). These materials could clog an adsorption column. Some pesticides (e.g., methoxychlor) can foul carbon beds (6). Consequently, dilute pesticide solutions containing these types of materials will require pretreatment before adsorption.

Finally, even at removal efficiencies of 98 percent or better, an influent of 500 ppm can still have an effluent of 10 ppm. For many pesticides, this concentration is potentially hazardous and further treatment will be necessary.

## Economics

Table 13 presents a cost estimate for a carbon adsorption treatment system. The major cost element is the pretreatment system, which can be eliminated if an applicator's dilute pesticide solutions consistently contain no suspended matter, emulsified pesticides, inorganic matter, or the few pesticide types that can foul a carbon system. Aside from that, major cost elements are the initial set-up and the annual operating expenses. Costs include the disposal of the spent carbon.

## BIOLOGICAL TREATMENT

Biological treatment systems rely on the microbial breakdown of organic pesticides to innocuous compounds. Although other treatment methods, such as land cultivation and evaporation basins, depend at least in part on biological degradation, the discussion in this section is limited to biological activity in an artificially-controlled environment. The principal methods to be discussed are activated sludge and trickling filter. However, the basic principles and the applicability of biodegradation to specific pesticides apply to all biological systems.

Almost all organic compounds can be broken down biologically, given the proper environment and sufficient time (69). Days or weeks may be required to obtain significant decomposition of some pesticides, and the breakdown of others may proceed so slowly that, for practical purposes, they may be considered nonbiodegradable. Pesticide characteristics that affect biodegradability include molecular weight, configuration, and bulkiness; elemental composition; and the type and location of substituent and functional groups on the molecule (69). Certain parts of a pesticide molecule may degrade more readily than other parts. For instance, the toxic group of a molecule may resist degradation, leaving a metabolite as toxic as the parent compound.

In general, aromatic compounds are more resistant to biodegradation than aliphatic and alicyclic compounds. The presence of elements other than carbon in the skeletal chain or ring may make the structure more degradation resistant. For example, esters and acid salts are usually less susceptible to breakdown than simpler compounds without these functional groups (60). Halogens on an aromatic ring increase resistance to biodegradation; chlorophenols become increasingly resistant with increasing halogen substitution. On the other hand, amino and hydroxy substitutions tend to increase biodegradability (69).

## TABLE 13. CARBON ADSORPTION COST ESTIMATE*

Basis for Calculations

1.7 $m^3$ (450 gal)/day
385 $m^3$ (102,000 gal)/yr
225 operating days/yr
120 min contact time
227 kg (500 lb) carbon/yr

| | | |
|---|---|---|
| **Capital Costs** | | |
| Holding tank | | $ 1,750 |
| Pump | | 470 |
| Pretreatment tank | | 1,300 |
| Filter and vacuum pump | | 7,000 |
| Carbon column pump | | 250 |
| Carbon column (3 m x 0.6 m) | | 600 |
| Initial carbon charge | | 750 |
| Installation, piping, electrical | | 4,450 |
| Contingencies | | 1,750 |
| Engineering | | 1,750 |
| | Total | $20,070 |
| **Yearly Operating Costs** | | |
| Monitoring | | $ 600 |
| Carbon | | 1,200 |
| Pretreatment chemicals | | 1,050 |
| Labor (500 hr @ $11/hr) | | 5,500 |
| Utilities | | 250 |
| Fixed charges (25% of capital cost) | | 5,018 |
| Spent adsorbent disposal | | 500 |
| | Total | $14,118 |

Operating costs per $m^3$ - $36.67
per gal - $ 0.14

* Carbon adsorption equipment costs are from Process design manual for carbon adsorption (67) updated to 1978. With standard engineering construction cost indices. The remaining cost elements are from Means Building Construction Cost Data 1978.

## Trickling Filters

Trickling filters are beds packed with various kinds of high surface area media upon which biological slimes develop. Wastewaters are sprayed on top of the bed and allowed to trickle through by gravity (Figure 12). As the wastes pass through the bed, the organisms in the slime layers metabolize organic matter present in the waste (Figure 13). The term filter is a misnomer; the removal of organic material is not accomplished through a physical filtering or straining operation, but is the result of an adsorption process at the biological slime surface followed by metabolization by the slime organisms (60).

## Activated Sludge

Activated sludge treatment is the biological oxidation of organic wastes in a reactor containing a concentrated biomass supplied with nutrients and oxygen in the proper ratio for efficient use of the waste by the organisms (Figure 14). Most organics, including pesticides, solvents, and by-products, can be utilized by bacteria under proper conditions. Utilization rate and removal efficiency vary for each compound and class of compounds.

Both trickling filter and activated sludge systems require construction of special tanks as well as special operating equipment. At least two operators skilled in the theory and operation of biological treatment systems are needed for each unit. Since dilute pesticide solutions do not contain sufficient nutrients to support bacterial growth, nutrients must be added to the system. Special monitoring devices are needed to control temperature, pH, nutrient content, and other factors.

Trickling filters and activated sludge are both used in industry to treat pesticide manufacturing wastes (60, 62). Trickling filters are generally used as a roughing filter, since they can handle fluctuating waste loads or slug flows with less chance of long-term upset than can other biological treatment systems (59). There has been little research to determine which pesticides are readily amenable to biological treatment. Chlorinated herbicide wastes can be successfully treated with trickling filter, while organic-phosphorus and 2,4-D wastes are amenable to activated sludge (60).

## Advantages

Under ideal conditions, biological treatment systems can give virtually complete pesticide detoxification (69). Even under less than ideal conditions, biological treatment has the

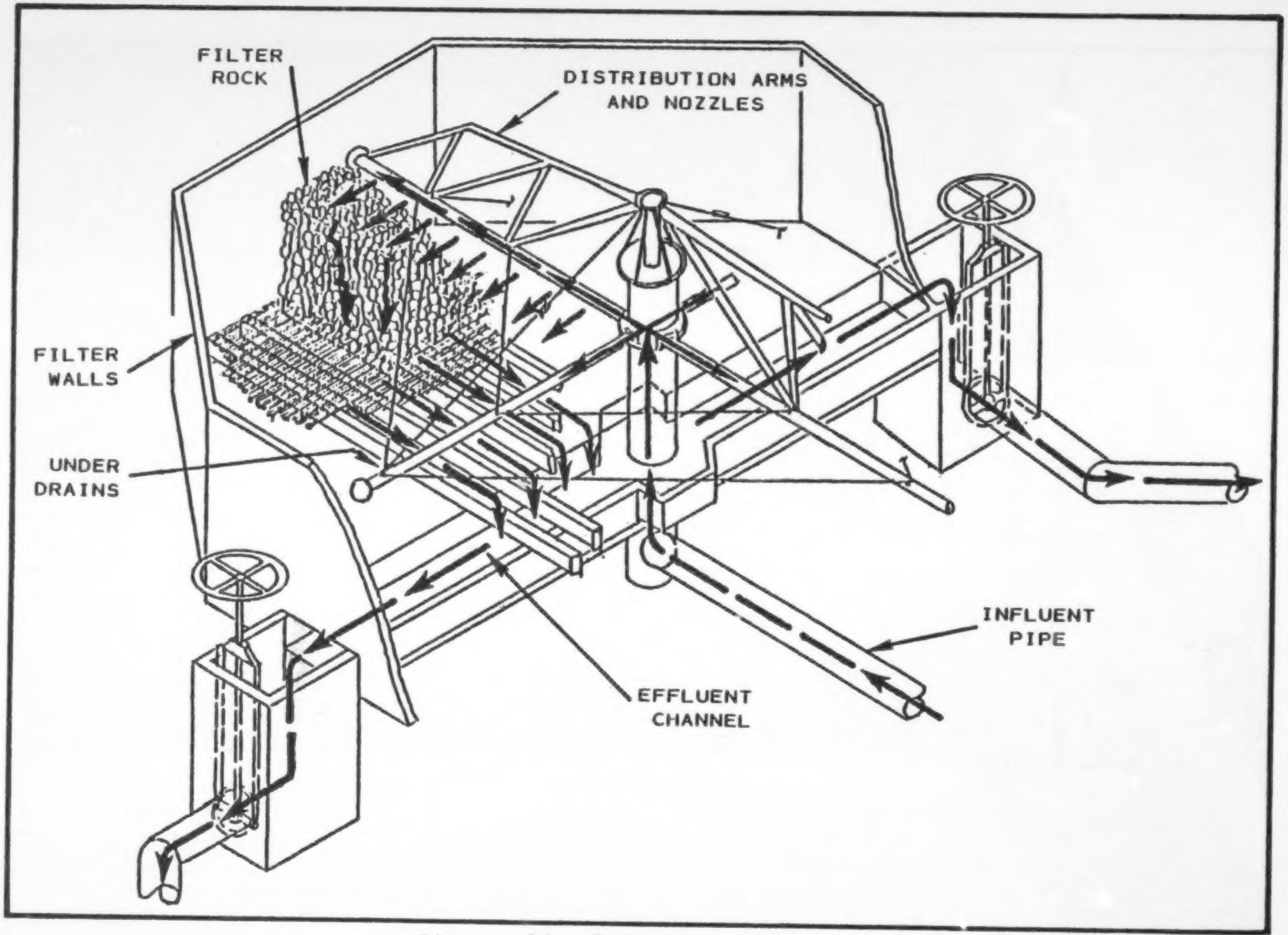
FILTER ROCK
DISTRIBUTION ARMS AND NOZZLES
FILTER WALLS
UNDER DRAINS
INFLUENT PIPE
EFFLUENT CHANNEL

Figure 12. Trickling filter.

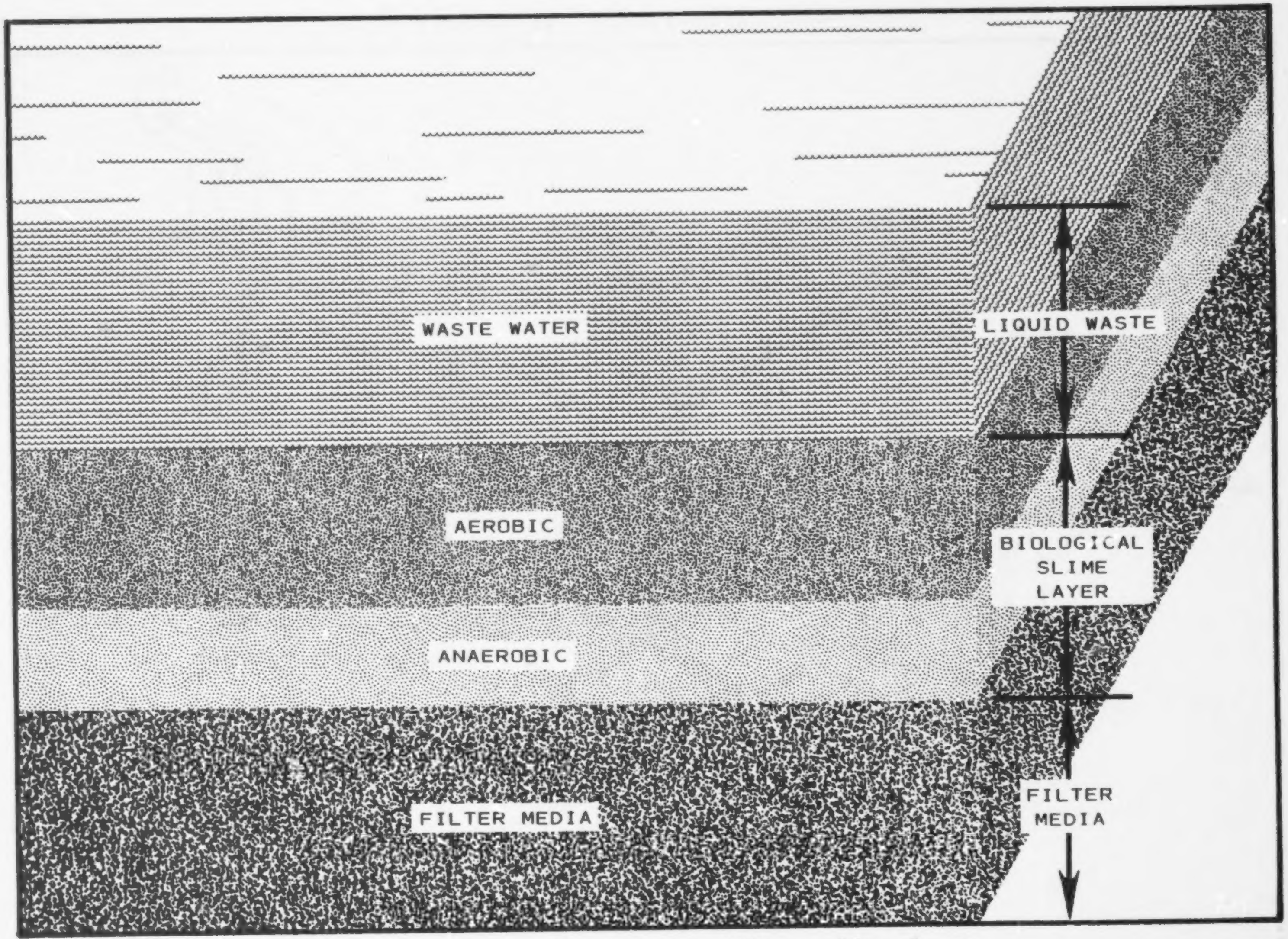
WASTE WATER
AEROBIC
ANAEROBIC
FILTER MEDIA
LIQUID WASTE
BIOLOGICAL
SLIME
LAYER
FILTER
MEDIA

Figure 13. Typical trickling filter slime layer.

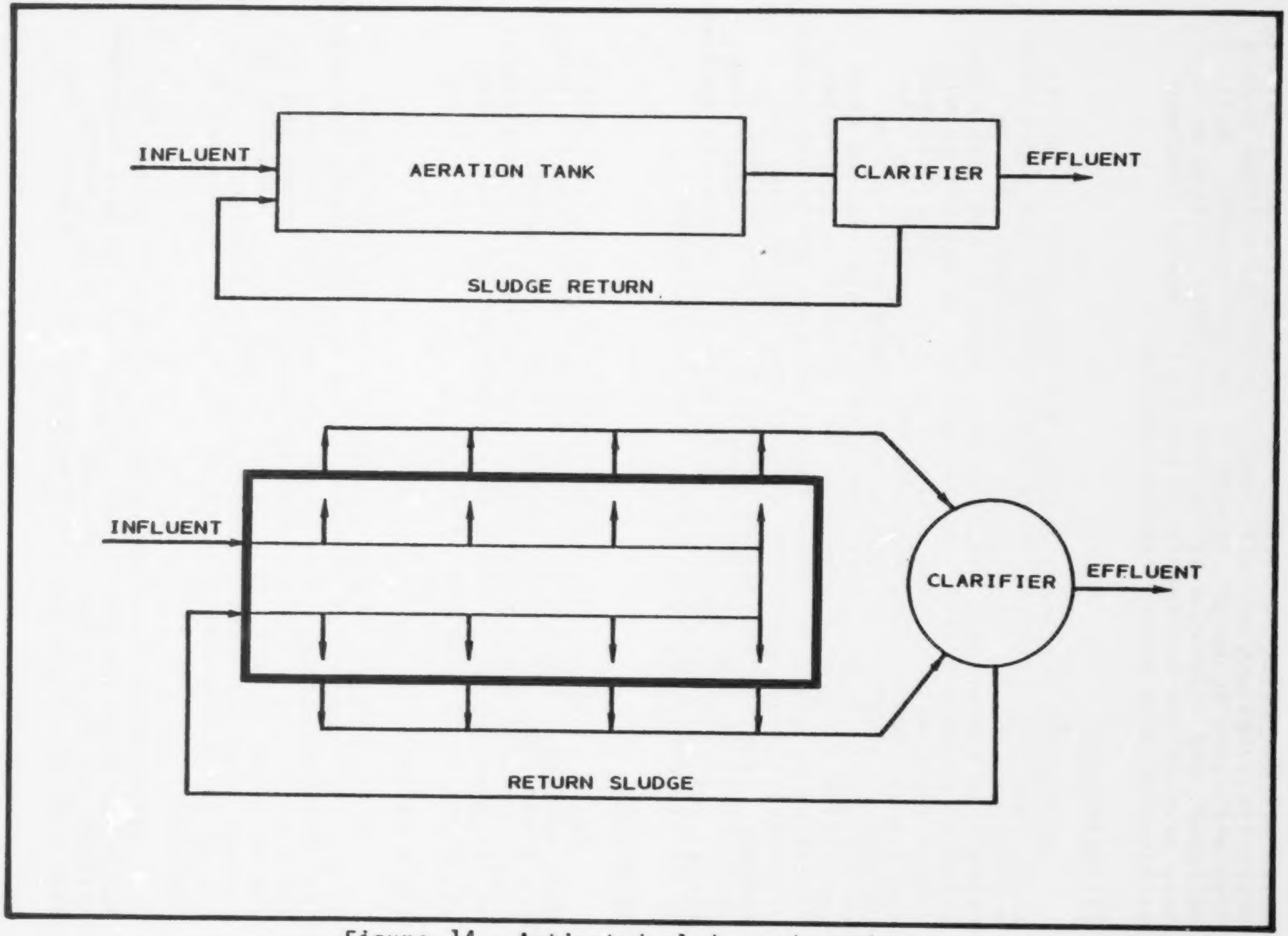
INFLUENT
AERATION TANK
CLARIFIER
EFFLUENT
SLUDGE RETURN
INFLUENT
CLARIFIER
EFFLUENT
RETURN SLUDGE

Figure 14. Activated sludge schematic.

potential for reducing toxicity and organic content in dilute pesticide solutions and eliminating pesticide residue traces from effluents to be discharged to the environment. Well-designed, and -operated biological treatment systems do not have many of the environmental and public health problems encountered with other treatment methods.

Disadvantages

Biological treatment systems are specialized, complex units requiring specific operating conditions and especially trained personnel. The systems are highly sensitive to changes in temperature, pH, nutrient content, and pesticide chemical structure (60). Consequently, the systems do not always adapt well to cold climates or areas where frequent and extreme temperature fluctuations are encountered. In general, biological systems do not respond well to wide variations in loading rates nor sudden changes in the concentration or type of pesticide in the waste to be treated. Furthermore, given the toxic nature of some pesticides (e.g., organometallics), bacterial die-off and system upset are common. Finally, degradation efficiencies and degrees of detoxification have not been determined for most pesticides; hence, the ultimate efficacy of biological systems, as applied to dilute pesticide solutions, is largely unknown.

Economics

Table 14 presents cost estimates for biological treatment systems. Roughly one-third of the capital costs are for the pretreatment systems. Unlike adsorption systems, pretreatment with biological treatment is virtually unavoidable; it is essential to ensure a fairly uniform influent. Cost estimates do not include land.

## INCINERATION

Incineration is waste processing (volume reduction) by means of controlled combustion, so that the waste components are converted to inorganic gases and solid ash residues. Incineration is a basic procedure recommended by the EPA for the disposal of waste organic pesticides (70). Research has demonstrated that, under proper operating conditions, virtually all of the active ingredients of organic pesticides can be degraded by incineration (71).

Incineration is a common waste processing method for municipal solid wastes, industrial wastes, and many hazardous wastes. It is the favored waste disposal method among pesticide manufacturing plant managers (60). However, most

## TABLE 14. BIOLOGICAL TREATMENT COST ESTIMATES*

### Basis for Calculation

$1.7\ m^3$ (450 gal)/day
$385\ m^3$ (102,000 gal)/yr
225 operating days/yr

### Capital Costs

| | Activated Sludge | | Trickling Filter |
|---|---|---|---|
| Holding tank | $ 1,750 | | $ 1,750 |
| Pump | 600 | | 600 |
| Reaction tank | 4,500 | Trickling filter | 4,000 |
| Aeration pump system | 1,500 | Recirculation system | 2,500 |
| Sludge recirculation system | 2,500 | | |
| Pretreatment system | 8,300 | | 8,300 |
| Piping | 1,750 | | 1,750 |
| Fencing | 700 | | 700 |
| Total | $21,600 | | $19,600 |

### Yearly Operating Costs

| | Activated Sludge | Trickling Filter |
|---|---|---|
| Monitoring | $ 600 | $ 600 |
| Electricity | 300 | 300 |
| Chemicals | 1,200 | 1,200 |
| Labor (1,000 hr @ $12/hr) | 12,000 | 12,000 |
| Fixed charges (25% of capital cost) | 5,400 | 4,900 |
| Sludge disposal | 1,500 | 750 |
| Total | $21,000 | $19,750 |
| Operating cost per $m^3$ - | $54.54 | $51.30 |
| per gal - | $ 0.20 | $ 0.19 |

---

* Equipment and operating cost are based on Means Building Construction Cost Data 1978.

industrial incineration involves waste pesticides and other manufacturing wastes of high organic content. Incineration of pesticide-containing wastewaters is confined to a few chemical manufacturing complexes and contract waste disposal services (55).

Figure 15 illustrates the basic design of a pesticide incinerator. There are several incinerator types, differing in configurations, efficiencies, and waste handling capabilities. A few designs are capable of handling liquid wastes. In all cases, the intent is that the waste have a high enough organic content to make the combustion self-sustaining. Otherwise, costly fuels must be used, which can make the system uneconomic.

Whatever incinerator design is chosen, it must have the following features:

- Adequate mixing of waste, oxidant, and auxiliary fuel
- Adequate residence time in the flame (2 sec)
- Adequate temperature for complete destruction of the pesticides and any toxic by-products formed during combustion (1000°C) (70).

To meet air quality regulations, incinerator stacks should be equipped with scrubbers or other air pollution control devices capable of removing at least 99 percent of the hazardous emission components; continuous monitoring devices should be placed on the stack to ensure that emission standards are being met. Scrubber effluent should be retained or impounded prior to release and tested to ascertain whether it meets water discharge standards or if treatment is required.

Because of the high temperatures involved and the corrosiveness of some of the waste gases (e.g., hydrochloric acid from chlorinated hydrocarbons), interior incinerator components must be replaced often if the incinerator is used extensively. Depending on the design, frequent maintenance may be required to keep waste feed lines and injection nozzles clear. This may be especially troublesome with a variety of waste types, compositions, and volumes.

Two to three operators are required. Special training is needed to ensure efficient combustion at minimum expense. Expertise is required to bring an incinerator to combustion temperature without damaging the unit. Air pollution control device and stack monitoring equipment operation also require special training.

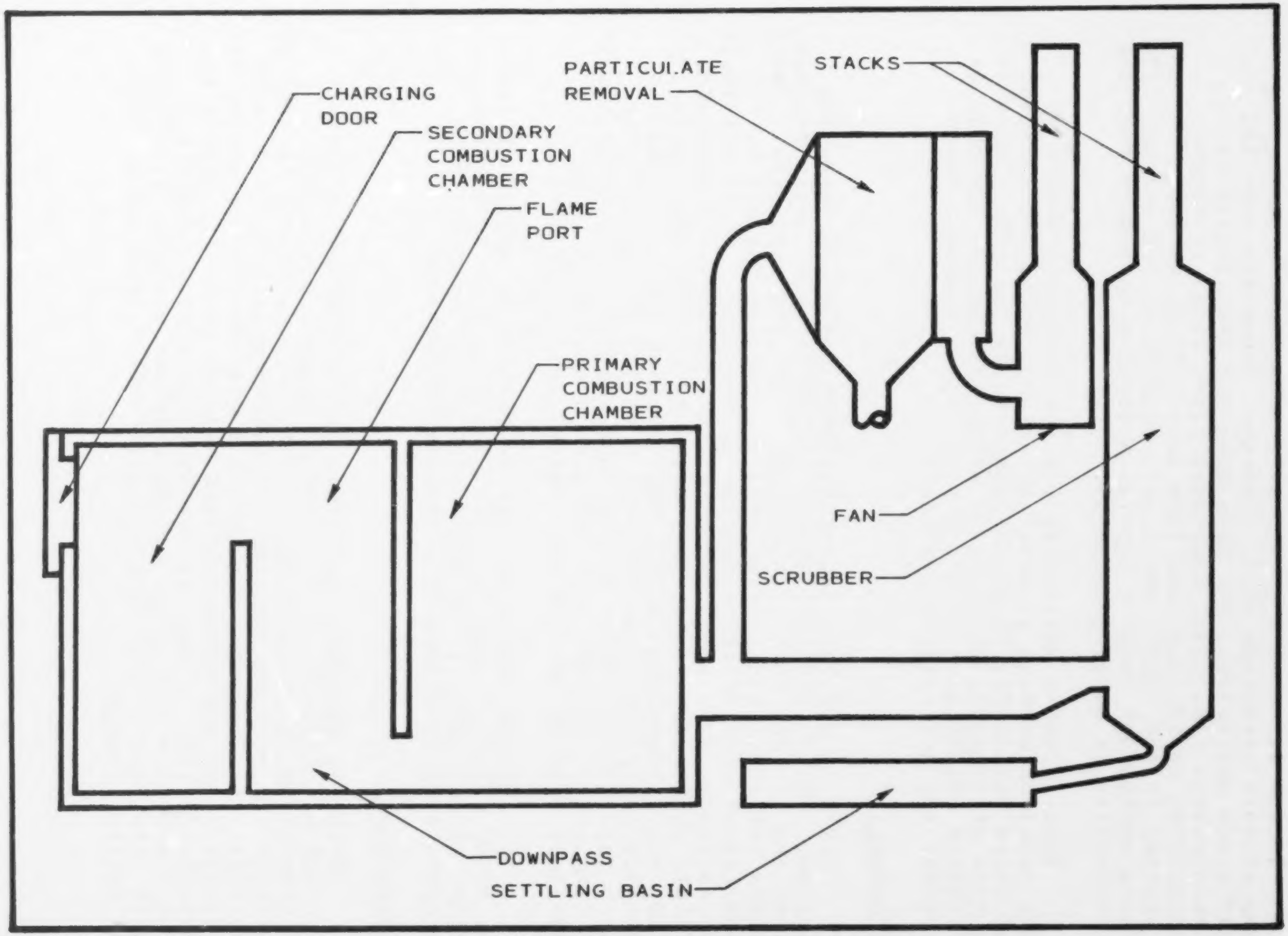
CHARGING DOOR
SECONDARY COMBUSTION CHAMBER
FLAME PORT
PRIMARY COMBUSTION CHAMBER
PARTICULATE REMOVAL
STACKS
FAN
SCRUBBER
DOWNPASS
SETTLING BASIN

Figure 15. Basic incinerator schematic

Incineration is theoretically effective in destroying any organic pesticide (71). However, there are over 500 different pesticides, and many have not been tested in incinerators (18, 72). Some pesticides (e.g. nitrogen-containing pesticides) can form toxic off-gases (e.g. cyanide) if the 1000°C and 2 sec. conditions are not met (72). These pesticides require special attention to ensure that the incinerator is working properly.

Metal organic pesticides are not readily amenable to incineration because of metal emissions; thus, incineration of these pesticides is not recommended by the EPA. There is a type of slagging incinerator which can recycle scrubbed or filtered metals back into the slag (72). However, these systems are not readily available.

## Economics

Table 15 presents a cost estimate for an incineration system. The incinerator itself is the largest single expense, then the air pollution control equipment and chemicals. These costs reflect typical industrial systems and may not be indicative of a dilute pesticide incinerator. It is difficult to estimate the cost differences, if any, because, although dilute pesticide incinerators might be smaller and simpler, they would represent special construction and a limited application piece of equipment and could, accordingly, be more expensive. Use of mobile incinerators may be possible in a farm area. Capital cost for such a system would be at least as much as for the stationary type costed here.

The largest operating expense element is auxiliary fuel. As noted above, enough fuel must be used to drive off the water and to combust the pesticides at sufficiently high temperatures to effectively consume the material.

## Advantages

Properly designed, operated, and maintained incinerators can achieve complete destruction of organic pesticides. Incineration is an existing, viable, well-developed technology without the problems inherent in experimental or pilot scale methods. Incinerators can handle a wide variety of pesticides, formulations, and concentrations and are generally stable and dependable (62). They can be installed almost anywhere, require little land area, can be operated without interfering with other operations, and are not readily upset by climate or weather changes.

## TABLE 15. INCINERATION COST ESTIMATE*

### Basis for Calculation

1.7 $m^3$ (450 gal)/day
385 $m^3$ (102,000 gal)/yr
225 operating days/yr

### Capital Costs

| | | |
|---|---|---|
| Holding tank | | $ 1,750 |
| Pump | | 600 |
| Incinerator (540 kg (1,200 lb)/hr) | | 58,200 |
| Air pollution control equipment | | 29,000 |
| | Total | $89,550 |

### Yearly Operating Costs

| | | |
|---|---|---|
| Monitoring | | $ 600 |
| Fuel oil [2.7 $m^3$ (700 gal)/day (13, 78); @ $0.25/gal] | | 40,000 |
| Chemicals | | 10,000 |
| Electricity | | 500 |
| Labor (2,000 hr @ $16/hr) | | 32,000 |
| Fixed charges (25% of capital cost) | | 22,388 |
| Ash and scrubber sludge disposal | | 1,000 |
| | Total | $106,488 |

Operating costs per $m^3$ - $277
per gal - $ 1.04

---

* Equipment and operating costs based on Means Building Construction Cost Data 1978 and Arthur D. Little, Economic analysis of pesticide disposal methods (12) updated to 1978 with standard engineering construction cost indices.

## Disadvantages

Incinerators, like any piece of complex machinery, have a greater tendency to malfunction than simpler systems. If incinerators are not operated within strict observance of acceptable operating procedures, combustion and stack gas control can become inefficient resulting in possible toxic emissions into the air.

Most incinerators presently in use are large-volume industrial and municipal units designed to handle low water content solid wastes. No specially designed dilute pesticide solution incinerators were identified during this study. Use of conventional incinerators would require dewatering of the waste stream or concentration before incineration.

Even with a dewatered or concentrated waste stream, an incinerator would require firing with auxiliary fuel to evaporate the remaining water before the pesticide itself could be consumed. Dilute pesticide wastes have a very low organic content and cannot support combustion without large quantities of auxiliary fuel. With high capital investments for the incineration equipment and control and monitoring devices, incineration can become very expensive.

## Transport and Incineration at a Central Facility

Given the current state of incinerator technology and economics, individual applicator owned and operated incinerators is not a viable alternative. Both capital and operating costs are prohibitive. Special skills and training are a necessity. Finally, neither the incinerators nor the support services necessary to maintain them are readily available to rural applicators.

However, incineration cannot be dismissed. It is a proven technology with a high pesticide destruction potential. One possible solution is to transport the wastewaters to a centrally-located public incineration facility. This option removes the burden of proper treatment and disposal from the applicator.

A central incineration facility reduces many of the disadvantages of incineration. A central facility, by accepting a large quantity and variety of wastes, could minimize the requirements for auxiliary fuel. It could better support the trained personnel needed than could an applicator-operated facility. By maintaining a permanent, full-time staff, overall supervision of the operation of the incinerator is more certain than with an applicator who has more varied, and to him more pressing, demands on his time.

The concept of a central treatment facility is not limited to incineration, although incineration of dilute pesticide solutions is. Central facilities could employ any appropriate treatment technology, including chemical and biological treatment or secure landfilling.

The advantages to the applicator include:

- Reduced need for additional treatment equipment, personnel, or labor costs
- Lower costs, even if all the transport costs are borne by the applicator

In terms of overall pesticide control, the fewer treatment systems in operation, the fewer number that can break down (although breakdowns, if any occur, would possibly be more serious). Some applicators (e.g. Coastal Agricultural Chemicals, Oxnard, California) currently use central hazardous waste disposal facilities successfully.

On the negative side, there are very few such treatment facilities nationwide, as shown in Figure 16 (73-75). Thus, the option is not open to most applicators. Most hazardous waste treatment facilities are located to serve industrial clients and seldom near agricultural areas.

Even if the facilities were readily available, the increased traffic in hazardous wastes raises the spectre of hazardous spills (76-77). The relative degree of hazard from spills versus applicator-operated treatment systems has not been evaluated.

## MISCELLANEOUS

As noted, most of the problems of dilute pesticide solution disposal are due to large volume. Thus, any practice that would serve to reduce the volume would also reduce the severity of the disposal problem. For instance, if pesticide containers were triple-rinsed and the rinsate mixed with the pesticide solution to be sprayed, there would be no container rinsate, no hazardous container disposal problem, and all of the pesticide would be used (1). Triple rinsing is now recommended by the EPA (70).

One proposal to eliminate the problem of excess dilute pesticide solutions and reduce the volume of rinsate is chemical volume control using separate tanks for the pesticide and the mix water (78-79). The concentrated chemical and water are piped separately to the spray boom or to each nozzle. Boom and nozzle rinsing at the washpad could be eliminated

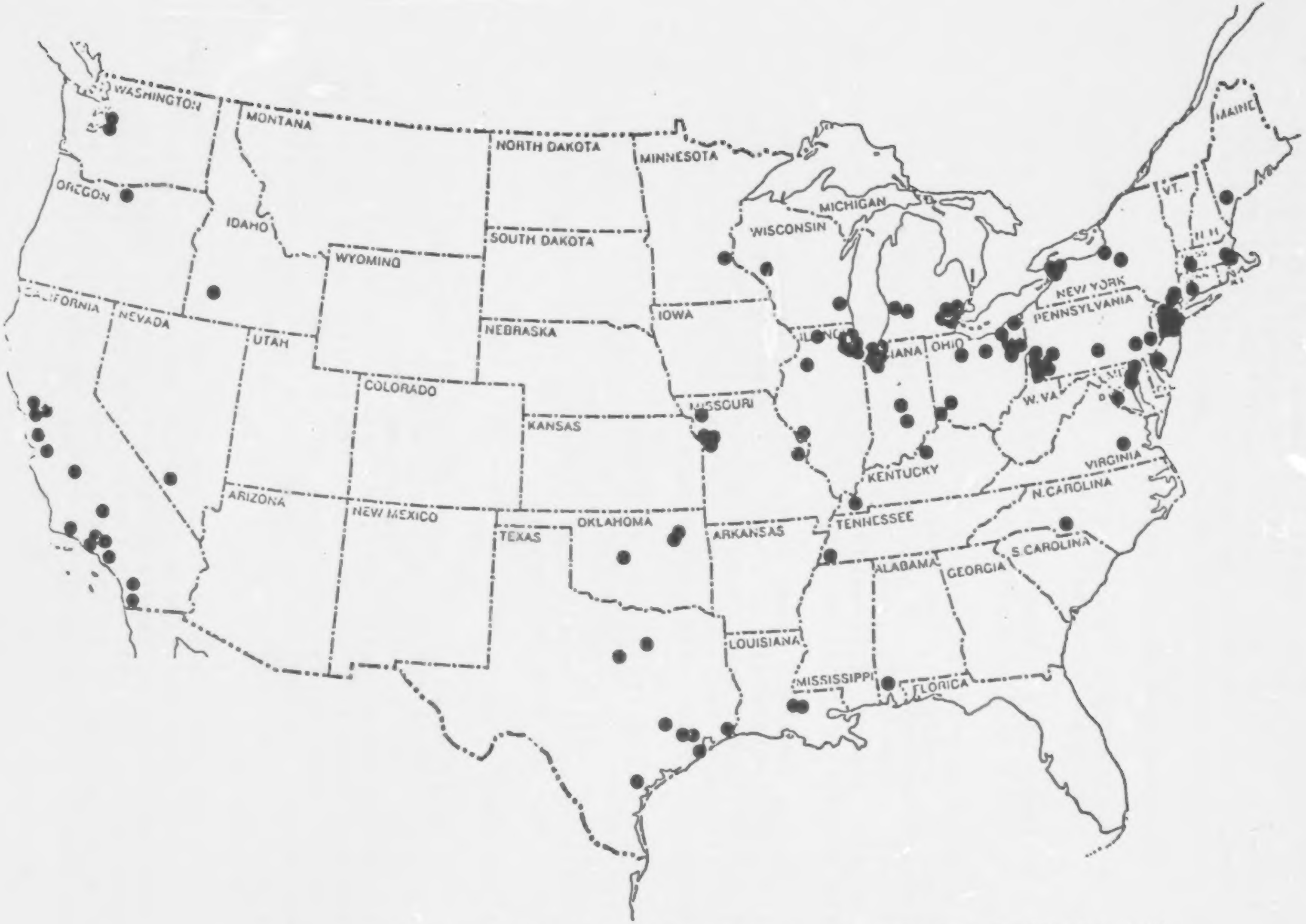
WASHINGTON
MONTANA
NORTH DAKOTA
MINNESOTA
MAINE
OREGON
IDAHO
WISCONSIN
MICHIGAN
VT.
N.H.
SOUTH DAKOTA
WYOMING
NEW YORK
PENNSYLVANIA
CALIFORNIA
NEVADA
UTAH
NEBRASKA
IOWA
ILLINOIS
INDIANA
OHIO
COLORADO
MISSOURI
KANSAS
W. VA
VIRGINIA
KENTUCKY
N. CAROLINA
ARIZONA
NEW MEXICO
OKLAHOMA
TENNESSEE
TEXAS
ARKANSAS
S. CAROLINA
ALABAMA
GEORGIA
LOUISIANA
MISSISSIPPI
FLORIDA

Figure 16. Geographic distribution of hazardous waste management facilities (75).

by flushing the system with water after spraying. Only one small tank would need to be washed. The use of several tanks, each for a specific pesticide, could reduce this need, since any residual pesticide need not be washed out as it is now.

This procedure would still leave small volumes of rinsate and periodic equipment washdown wastewaters. It has been suggested that these dilute pesticide solutions could be collected and reused later as diluent in pesticide solution formulations (4). This may be impractical for several reasons. Many pesticides are chemically incompatible, and, generally, herbicides cannot be mixed with insecticides. Consequently, separate holding tanks would be necessary for different pesticide wastewaters. If an applicator uses many types of pesticides, he could become the manager of a virtual tank farm, and management problems could become unacceptable.

# CHAPTER 4

# COMPARATIVE EVALUATION OF METHODS

The ultimate universal waste disposal method capable of complete destruction of all wastes under all conditions while remaining safe and economical does not exist at the present time. None of the disposal or treatment methods discussed in this report is perfect, but one or more will probably be used to treat dilute pesticide solutions. All have advantages and disadvantages. The purpose of this chapter is to comparatively evaluate the methods against an ideal to:

- Clearly indicate which method(s) most closely approaches the ideal
- Highlight the relative strengths and weaknesses of each method.

In general, the ideal treatment or disposal method should:

- Not lead to impairment of air and water quality
- Not adversely affect wildlife or general environmental quality
- Not present hazards to operators or any nearby populace
- Be capable of reducing the toxicity of the pesticides to safe levels through degradation, or at least be capable of immobilization and containment
- Be applicable to all pesticides, formulations, and concentrations
- Not be susceptible to breakdowns, upsets, or frequent shutdowns
- Be readily available to all pesticide applicators
- Be relatively inexpensive and simple to operate.

The methods discussed in this report can be evaluated by determining the degree to which each meets these ideals. To simplify the evaluation, these factors can be reduced to five general criteria:

- Environmental Safety
- Effectiveness
- Pesticide Applicability
- Availability
- Applicator Factors.

Each of these criteria will be discussed in detail.

In the course of the evaluation, each method will be given a numerical "score" for each criterion reflective of its relation to the ideal. The total scores should indicate which methods have the most promise and the individual criterion scores should indicate what areas of research are most appropriate for each method.

The six criteria are not weighted equally. They are biased in favor of environmental safety, pesticide applicability, and effectiveness. The "perfect" score for each criterion is:

- Environmental Safety - 55
- Effectiveness - 35
- Pesticide Applicability - 35
- Availability - 30
- Applicator Factors - 20

In the following discussions it should be noted that several factors may go into determining the scoring for each criterion. The numerical scores given each factor within each criterion bear no relation to any factor within any other criterion. The individual factor scores relate only to the other factors within a criterion. Factors from different criteria should not be compared, only the total value for the criteria. This should become clearer in the following discussions.

The following assumptions, limitations, and choices regarding the methods were used for the evaluation:

- All washdown pads are equipped with drains and holding tanks; volume to be treated can thus be regulated to provide a constant flow rate.

- Appropriate safety precautions (fencing, warning signs, locked storage, safety devices) are used at each disposal site. This does not mean that accidents will not happen, but for this discussion the role of random accidents was not considered.

- Proper site selection and operational procedures are followed at each site.

- Standard pollution control measures (e.g., scrubbers on incinerator stacks) are in use at all sites.
- With the exceptions noted below, all methods are located near, and operated by, individual agriculture custom applicator companies in rural areas.
- Land cultivation sites are unlined and the pesticides are applied by means of a single tractor injection system.
- Soil mounds and pits and evaporation basins are lined with a dual liner (concrete over plastic) and are roofed.
- In general, each method is operated as previously described in the text.
- Incineration is not considered feasible for individual applicators; thus, incineration in the following evaluations is based on transport of the dilute pesticide solutions by the applicator to a central incineration facility.

## ENVIRONMENTAL SAFETY

There are four factors in determining environmental safety: protection of water quality, protection of air quality, public safety, and prevention of contact with domestic animals or wildlife. Air and water quality factors are scored as follows:

20 - minimal possibility of quality impairment due to migration of pesticide away from the treatment system

15 - some quality impairments possible under certain conditions

10 - existing data regarding the degree of hazard incurred when using this method with dilute pesticide solutions contradictory or insufficient; there may or may not be a hazard

5 - significant movement of pesticides or degradation product from the treatment system to the environment is likely with possible quality degradation.

Public safety refers to the hazards not related to air or water quality presented by the method. In general, it refers to such hazards as fire or explosion or hazards from accidental contact by people. Public safety is scored as follows:

10 - closed system with no fire or explosion hazards

7 - open system with contact with pesticide dose possible
4 - treatment process may present a fire or explosion hazard.

Prevention of pesticide contamination of animals is scored as follows:

5 - contact unlikely
3 - contact with burrowing animals or birds possible.

Table 16 shows the scores of the treatment methods for these factors and the total scores for environmental safety.

There is considerable controversy over the degree to which pesticides or pesticide degradation products will migrate in soil during land cultivation. A number of references can be drawn up to support both sides of the issue (22-50): (1) most pesticides will not migrate through the soil but will degrade on-site or (2) migration to ground or surface waters is possible (6, 19-43, 45, 80). A similar controversy exists in regard to the degree of pesticide loss from soil through volatilization. It seems likely that both migration and volatilization are related to concentration of the pesticide in the soil, the type of pesticide, the type of soil, the soil moisture content, and so forth. The exact relationships and limitations have not been clearly defined.

Land cultivation, even at enclosed sites, is open to birds and many burrowing animals. Should the fences be damaged, land cultivation could present a hazard to wildlife and domestic animals.

Soil mounds and pits do not fare equally well in terms of overall environmental safety. Given a dual layer liner (e.g., plastic and concrete), both are unlikely to contaminate groundwater supplies. In terms of air emissions, the impact of soil mounds is unknown. The results available to date regarding air emissions from soil mounds are not sufficient for an evaluation. On the other hand, soil pits, with their open tops and method of dilute pesticide solution addition present a clear air quality hazard. The degree of the hazard is not known, but the potential for harm is there. Soil mounds, being a closed system, are secure from inadvertent contact with the pesticides. Soil pits, being open, could present a minimal hazard, but surface concentrations should be slight. The same reasoning generally holds true for animal contact. In both cases the scores will drop if less secure liners, (e.g., clay or single layer polymer) are selected.

Evaporation basins generally do not present a water quality hazard because the pesticide solutions are contained. However, they present a definite air quality hazard, as evidenced from the many residents who complain of odors from the evaporation basins. Since they are open systems, contact with the pesticides is possible.

Chemical treatment can be a closed system during operation, making it essentially safe from animal contact or air emissions.

TABLE 16. ENVIRONMENTAL SAFETY

| Method | Air Quality* | Water Quality* | Public Safety† | Animal Life ‡ | Total |
|---|---|---|---|---|---|
| Land cultivation | 10 | 10 | 7 | 3 | 30 |
| Soil mounds | 10 | 20 | 10 | 5 | 45 |
| Soil pits | 5 | 20 | 7 | 3 | 35 |
| Evaporation basins | 5 | 20 | 7 | 3 | 35 |
| Chemical treatment | 15 | 15 | 10 | 5 | 45 |
| Biological treatment | 15 | 15 | 7 | 3 | 40 |
| Adsorption | 20 | 20 | 10 | 5 | 55 |
| Transport and incineration | 15 | 15 | 4 | 5 | 39 |

Score values:

*20 - minimal possibility of impairment from pesticide migration away from the system
15 - some quality impairments possible under certain conditions
10 - existing data insufficient to evaluate degree of hazard
5 - significant movement or quality impairment possible.

†10 - closed system with no fire or explosion hazard
7 - open system with contact with pesticide dose possible
4 - treatment process may present a fire or explosion hazard

‡ 5 - contact unlikely
3 - contact with burrowing animals or birds possible.

Since 100 percent degradation is unlikely, some contamination of receiving waters due to residual pesticides or reaction products is possible. Most treatment chemicals present a hazard to untrained personnel, and the use of strong oxidizing agents can present an explosion hazard.

Most biological wastewater treatment units are open to the atmosphere and emissions are possible. Water quality impairment from degradation products or refractory pesticides in the effluent is also possible. Being open units, contact with animal life or unauthorized persons is possible. The hazard is not generally as great with biological treatment as with evaporation basins because the concentration factor is not at work.

Adsorption is a completely closed process and, if operated properly, can achieve a high degree of treatment. It appears to have the fewest possibilities for environmental damage of any of the methods discussed.

Transport to a central incinerator facility suffers in terms of air and water quality, not because of the incineration, which is highly safe on both counts, but because of the spill possibilities discussed earlier. If this method becomes popular, the hazard could even increase because of the increased number of "pesticide miles." Spills can cause public safety problems, but the rating for public safety is based primarily on the explosion and fire hazards inherent in the incineration process.

## EFFECTIVENESS

There are two factors involved in effectiveness: (1) extent of degradation and (2) in the case of incomplete degradation, containment of pesticides or pesticide degradation products. Effectiveness takes into account the fact that "contained" pesticides will require further treatment or disposal through lower scores for containment than degradation. Containment in this case means essentially no uncontrolled movement of pesticides or products away from the treatment system. In scoring the methods, complete degradation is also scored as complete containment. The factors are scored as follows:

Degradation 20 - 98+ percent degradation of the pesticides and degradation products is possible

15 - a high degree (75 to 98 percent) of degradation is likely

10 - 50 to 75 percent degradation is possible

5 - degradation effectiveness is unknown

0 - no degradation likely.

Containment 15 - pesticides and degradation products totally contained

10 - some minimal migration possible

5 - degree of containment unknown

0 - no containment likely.

Table 17 shows the scores of the treatment methods for these factors and the total effectiveness scores.

As noted earlier, the data on the effectiveness of land cultivation are not sufficient to predict the outcome for many disposal situations; neither degradation or containment has been adequately determined. The lack of knowledge regarding the degree of degradation also extends to soil mounds, soil pits, and evaporation basins. Soil mounds, a closed system, represent an attempt at total containment. Both soil pits and evaporation basins, being open, have a possible atmospheric movement route. Chemical treatment can achieve a very high degree of treatment, but there can be pesticide residuals in the effluent. Biological treatment can achieve a high degree of degradation but, again, the possibility of residuals in the effluent is present. Adsorption does not degrade pesticides (aside from whatever atmospheric oxidation or natural hydrolysis may occur) but it does contain them, effectively reducing the overall volume of wastes to be dealt with later. Incineration is highly effective in destroying organic pesticides. (Note: The effectiveness ratings for incineration do not take into account reduced containment during spills; this was dealt with under Environmental Safety and a lesser rating for incineration here could be misleading as to its true effectiveness). All of the effectiveness scores assume that the individual treatment methods are not used to treat pesticides which have been demonstrated untreatable by those methods.

## VERSATILITY OF METHOD

The versatility of the treatment methods involve the types, forms, and concentrations of pesticies considered treatable by the method. Consequently, the factors used to score applicability are pesticide chemical class, concentrations, and formulations.

Pesticide chemical class refers to the ability of the treatment method to accept any type of pesticide into the system. It says nothing about the degree of treatment nor does it assume that all acceptable types can be treated to an equal extent. It merely refers to whether some degree of treatment can be expected. It is scored as follows:

15 - can accept virtally any pesticide with no change in operating conditions

TABLE 17. EFFECTIVENESS

| Method | Degradation[*] | Containment[†] | Total |
|---|---|---|---|
| Land cultivation | 10 | 5 | 15 |
| Soil mounds | 5 | 15 | 20 |
| Soil pits | 5 | 10 | 15 |
| Evaporation basins | 5 | 10 | 15 |
| Chemical treatment | 20 | 10 | 30 |
| Biological treatment | 15 | 10 | 25 |
| Adsorption | 0 | 15 | 15 |
| Transport and incineration | 20 | 15 | 35 |

Score values:

[*] 20 - 98+ percent degradation of the pesticides and degradation products is possible.
15 - a high degree (75 to 98 percent) of degradation is likely.
10 - 50 to 75 percent degradation is possible.
5 - degradation effectiveness is unknown.
0 - no degradation likely.

[†] 15 - pesticides and degradation products totally contained.
10 - some minimal migration possible.
5 - degree of containment unknown.
0 - no containment likely.

10 - can accept virtually any pesticide but changes in operating conditions necessary

5 - several commonly used pesticides cannot be treated by this method.

Given the assumptions made at the beginning of this section, all methods are preceded by a holding tank which keeps the volume feed rate constant. Because of differences in application rates or washing procedures, pesticide concentrations may vary, however. The effect this variable will have on operations is scored as follows:

10 - changes in concentration will neither require changes in operations nor affect the treatment efficiency appreciably.

5 - changes in concentration can necessitate operational changes or disrupt the treatment system.

All of the pesticides in dilute pesticide solutions are water-borne, but not all enter the water in the same form. Thus, the dilute pesticide solutions can indeed be solutions or they can be suspensions or emulsions. The wastewaters can contain oils, sulfur, or inert carriers such as clay. Whether or not this can affect the treatment method is scored as follows:

10 - the system will continue to function regardless of the formulation

5 - certain formulations can necessitate pretreatment systems.

Table 18 shows the scores of the treatment methods for these factors and the total applicability scores.

Land cultivation, soil mounds and pits, and evaporation basins are natural systems with few adjustable variables once system operation has commenced. In general, changes in the quality of the dilute pesticide solutions are unlikely to adversely affect the effectiveness of the system for any extended period of time. However, there are a few limitations. Mixing some incompatible pesticides can increase hazards due to toxic gas formation. In such cases it may be necessary to alter operating conditions.

Land cultivation spreading rates could be affected by changes in pesticide concentrations in the wastewater. Many industrial users of evaporation basins prefer to remove inert material to prevent excessive sludge build-up in the basins. Certain pesticides (e.g., metallo-organics or inorganics) and/or increasingly high concentrations of pesticides in the soil or water can affect

TABLE 18. VERSATILITY OF METHOD

| Method | Chemical Classes* | Pesticide Concentrations† | Pesticide Formulations‡ | Total |
|---|---|---|---|---|
| Land cultivation | 10 | 5 | 10 | 25 |
| Soil mounds | 10 | 10 | 10 | 30 |
| Soil pits | 10 | 10 | 10 | 30 |
| Evaporation basins | 10 | 10 | 5 | 25 |
| Chemical treatment | 10 | 5 | 5 | 20 |
| Biological treatment | 5 | 5 | 5 | 15 |
| Adsorption | 5 | 5 | 5 | 15 |
| Transport and incineration | 5 | 10 | 5 | 20 |

Score values:

*15 - can accept virtually any pesticide with no change in operating conditions
10 - can accept virtually any pesticide but changes in operating conditions necessary
5 - several commonly used pesticides cannot be treated by this method.

†10 - changes in concentration will neither require changes in operation nor affect treatment efficiency appreciable
5 - changes in concentration can necessitate operational changes or disrupt the system.

‡10 - system will continue to function regardless of the formulation
5 - certain formulations may necessitate pretreatment systems.

degradation rates significantly. However, since land cultivation, soil mounds and pits, and evaporation basins also serve as containment systems, the loss in degradation efficiency does not affect the overall operation of the systems.

The type of chemical treatment is highly dependent on the pesticide compound to be treated. Thus, a change in compound could conceivably require a complete shut-down, clean-up, and change-over to another form of chemical treatment. Changes in concentration will affect changes in chemical feed rates. Some formulations, such as emulsions, can require pretreatment if effective degradation is to be achieved.

Many common pesticides are highly toxic to the organisms in biological treatment systems. Even those pesticides which are only marginally toxic or to which the organisms have become acclimated can cause severe upsets if the pesticide concentrations increase suddenly. If biological treatment is to be effective, inert carriers, oils, alkalies or acids (e.g., lime, sulfur), and so forth will have to be removed before treatment.

Some pesticides, especially the oil-types, can foul adsorption beds. Furthermore, oil emulsions or insoluble particulate carriers or pesticides can clog beds, rendering them inoperative. Consequently, pretreatment is often necessary. Concentration changes affect the life of the bed and can necessitate changes in flow rates.

Neither pesticide formulation nor concentration can normally be expected to affect incineration (assuming that a supplemental fuel source is being used). There are certain pesticides (e.g., metallo-organics or inorganics) for which incineration is not recommended or is prohibited entirely. Certain metallo-organics can be incinerated after pretreatment to remove the metal component (40-CFR-165).

## AVAILABILITY

Availability refers both to the ability of the method to be implemented and the reliability of the methods themselves. A method which is in the experimental stage is not as valuable as one that represents a proven technology. Similarly a method which cannot be relied on is less useful than one which can. The factors used to assess availability are status, scope, and reliability.

Status refers to whether a method is operational or experimental or if it can be readily installed and operated by individual applicators. It is scored as follows:

10 - operational technology readily adaptable to operation by applicators

7 - operational technology not readily available to applicators but could be used in a central treatment facility

4 - experimental technology which could be implementable by applicators

1 - theoretical technology.

In evaluating availability, scope adds 5 points if a method could be adopted for use in urban environments by pest control operators.

Reliability assesses the amount of downtime which can be expected with a method. It is scored as follows:

15 - breakdowns, shutdowns, downtime unlikely

10 - periodic, routine maintenance shutdowns required

5 - occasional long downtimes expected which could seriously affect treatment of the dilute pesticide solution

0 - may be liable to frequent or unexpected breakdowns.

Table 19 shows the scores for these factors of the treatment methods and the total scores for availability.

Only soil pits and incineration are not readily available to applicators. The soil pit system as developed by Iowa State University is still an experimental design. Individual incinerators are simply too complex technologically and costly for individual applicators. Transport and incineration is limited by the small number of hazardous waste treatment facilities. All of the other methods are being used in agricultural areas either for pesticides or other wastes and could readily be adapted to dilute pesticide solutions and applicator operation. Space requirements and/or air pollution hazards prevent land cultivation, soil pits, evaporation basins, and biological treatment from being adapted for use by individual pest control operations in urban areas.

Only land cultivation has no inherent breakdown or shutdown problems. Tractor maintenance could be a problem but this could be solved by scheduling for weekends or lulls in spraying. Severely adverse weather conditions (e.g., heavy rains or freezing temperatures) could disrupt the operation of land cultivation systems, but since spraying is unlikely under these conditions, the overall reliability of the system may not be impaired. Soil mounds and pits require occasional complete shutdown so that the soil and residues in the systems can be

TABLE 19. AVAILABILITY

| Method | Status* | Scope† | Reliability‡ | Total |
|---|---|---|---|---|
| Land cultivation | 7 | 0 | 15 | 22 |
| Soil mounds | 7 | 5 | 10 | 22 |
| Soil pits | 4 | 0 | 10 | 14 |
| Evaporation basins | 7 | 0 | 10 | 17 |
| Chemical treatment | 10 | 5 | 10 | 25 |
| Biological treatment | 10 | 0 | 5 | 15 |
| Adsorption | 10 | 5 | 10 | 25 |
| Transport and incineration | 7 | 5 | 10 | 22 |

Score values:

*10 - operational and readily available to applicators
7 - operational but not necessarily available to all applicators
4 - experimental but could be implemented by applicators
1 - theoretical

† 5 - may be adaptable for use in urban environments by pest control operators.

‡15 - breakdowns, shutdowns unlikely
10 - periodic routine maintenance shutdowns required
5 - occasional long downtimes which could seriously affect treatment.

completely removed and replaced. Biological treatment is sensitive even under the best of conditions. Changes in pesticide type or concentration, pH, weather, or many other factors can upset even a properly operated system. The other systems need routine maintenance, but in general not much downtime. Evaporation basins require periodic sludge removal; chemical treatment tanks and equipment will need cleaning; adsorbents must be replaced; and incinerators will require periodic check-ups and part replacements.

## APPLICATOR FACTORS

Although not a factor in the usefulness of a treatment method, taking the industry as a whole, applicator acceptance will have a bearing on the actual effectiveness of a method. If an applicator objects to a given method, he may find ways to circumvent any regulations requiring its use. Consequently, a method should be as unobjectionable to the applicator as possible to ensure his cooperation.

It is possible to evaluate some tangibles which will have an impact on the applicator, namely labor and economics. Labor can be broken down into two component factors: man-hours and skill. Man-hours refers to the actual time of operation of the treatment method. This time will either reduce the man-hours of crop treatment time available or will add man-hours to the total labor requirements of the custom applicator. Skill considers the degree of training necessary to effectively operate a treatment method. In some cases extensive training will be needed, necessitating lost time from the actual spraying operations. These factors are scored as follows:

| | |
|---|---|
| Man-hours: | 5 - <8 man-hours weekly |
| | 3 - 8 to 24 man-hours weekly |
| | 1 - additional full or part-time people needed to operate system |
| Skill: | 5 - can generally be operated within the existing skills of the applicator |
| | 3 - some training required, on-the-job training usually sufficient |
| | 1 - extensive training required. |

In the case of transport and incineration, the labor requirements are based on filling the tank truck and driving to the disposal facility.

Economics is note scored like the other factors. Rather the least costly method is given ten points and the other methods are ranked accordingly, with scores decreasing as expenses increase. Capital costs are converted to a cost per $m^3$ figure over a ten-yr period and added to operating costs to get a total cost. Transport and incineration costs are incalculable because they will depend on travel distance and incinerator fees which could vary widely. Consequently, transport and incineration is ranked midway to avoid biasing the totals too greatly in any direction.

Table 20 shows the scores of the treatment methods for these factors and the total applicator factor scores.

Evaporation basins are generally the simplest and least costly system to build and operate. Soil pits and mounds are equally simple to operate, but somewhat more costly. Land cultivation requires greater skills, but these should be readily available in an agricultural community. Chemical treatment and adsorption require more time to operate, largely because of pretreatment requirements and more comprehensive training. Biological treatment is costly, can often need almost constant attention, and requires extensive training to be operated at optimum efficiency.

## SUMMARY

Table 21 presents the totals for each criteria and the total score for each method. A score of 175 would be perfect; no method comes close to that score. Three methods scored higher than 130, however: soil mounds, transport and incineration, and chemical treatment. Based on the scores, these would appear to be the most promising. However, all have problems. Soil mounds are still uncertain environmentally. With further research they could be eliminated as a potential method or moved still higher in the ratings. Transport to a central incineration facility is currently limited by the lack of commercial incinerator facilities capable of accepting dilute pesticide solutions. At present, chemical treatment suffers chiefly through its limited pesticide applicability and expense. Further research could correct these problems. As far as individual applicators are concerned, only biological treatment appears to be out of the running. Its high effectiveness scores suggest that it could conceivably be used in a central treatment facility.

Adsorption certainly pssesses promise. Its most apparent weaknesses are a low rating for effectiveness because of its nature as a contain-and-concentrate rather than degrade method, and its low rating for applicability. However, it is very effective as a contain-and-concentrate method. Soil pits and evaporation basins are in a nebulous place in the scorings - neither good nor excessively bad. Both suffer in terms of air

## TABLE 20. APPLICATOR FACTORS

| Method | Man-hours* | Skill† | Economics‡ | Total |
|---|---|---|---|---|
| Land cultivation | 5 | 5 | 7 | 17 |
| Soil mounds | 5 | 5 | 8 | 18 |
| Soil pits | 5 | 5 | 9 | 19 |
| Evaporation basins | 5 | 5 | 10 | 20 |
| Chemical treatment | 3 | 3 | 5 | 11 |
| Biological treatment | 1 | 1 | 2 | 4 |
| Adsorption | 3 | 3 | 3 | 9 |
| Transport and incineration | 3 | 5 | 6 | 14 |

Score values:

*5 - <8 man-hours weekly
3 - 8-24 man-hours weekly
1 - additional full or part-time people needed to operate system

†5 - can be operated within existing skills of the applicator
3 - some training required; on-the-job usually sufficient
1 - extensive training required.

‡10 - least expensive; all others ranked in order with score decreasing as costs increase.

TABLE 21. SUMMARY TABLE

SCORES OF DILUTE PESTICIDE SOLUTION DISPOSAL METHODS

| | Criteria | | | | | |
|---|---|---|---|---|---|---|
| Method | Environmental Safety* | Effectiveness | Pesticide Applicability | Availability | Applicator Factors | Total |
| Land cultivation | 30 | 15 | 25 | 22 | 17 | 108 |
| Soil mounds | 45 | 20 | 30 | 22 | 18 | 135 |
| Soil pits | 35 | 15 | 30 | 14 | 19 | 113 |
| Evaporation basins | 35 | 15 | 25 | 17 | 20 | 112 |
| Chemical treatment | 45 | 30 | 20 | 25 | 11 | 131 |
| Biological treatment | 40 | 25 | 15 | 15 | 4 | 99 |
| Adsorption | 55 | 15 | 15 | 25 | 9 | 119 |
| Transport and incineration | 39 | 35 | 20 | 22 | 14 | 130 |

*See chapter for explanation of criteria and scores.

quality degradation. The experimental status of soil pits also is a detriment. If they were to be made readily available, their score could climb into the 120's.

The potential of land cultivation as a dilute pesticide solution treatment method is still uncertain. Depending on the ultimate outcome of research into the movement and degradation of dilute pesticides in the soil, the total score for land cultivation could range from 85 to 155. Consequently, land cultivation cannot be dismissed out-of-hand because it may be both effective and environmentally acceptable under certain conditions. Its potential high score is such that further research is almost mandatory.

# CHAPTER 5

# CONCLUSIONS

The following conclusions are based on the information gathered in this study:

- The disposal of dilute pesticide solutions is an increasingly serious problem because of the volume of wastewater, the pesticide content, the lack of comprehensive guidelines regarding DPS treatment and disposal, and the possibility that the proper disposal of DPS may soon be required and regulated.

- Most dilute pesticide solutions are generated by agricultural pesticide applicators who should thus be the major objective of any control program; a secondary objective would be urban pest control operators.

- The treatment methods commonly considered most applicable for dilute pesticide solutions are land cultivation, soil mounds, soil pits, evaporation basins, chemical treatment, biological treatment, adsorption, and incineration.

- Land cultivation appears to be effective for readily degradable or adsorbable pesticides at low loading rates, but there are still too many environmental uncertainties regarding rates of degradation, migration, and volatilization; susceptible pesticides and concentrations; and optimum site characteristics to recommend it unqualifiedly. Further research is needed to fully identify its potentialities and limitations.

- Soil mounds and pits can be very effective at containing pesticides and degradation products and are relatively economic; thus, soil mounds and pits have a very high potential. On the negative side, soil mounds have not been extensively tested outside of California and soil pits are still in the experimental stage. Both require further research into volatilization rates and expected lifetimes.

- Evaporation basins are a popular industrial pesticide solution treatment method and are used by many Texas aerial pesticide applicators; crude basins are used informally in many other areas. They are subject to pesticide volatilization of unknown severity. Otherwise they are effective containment methods.

- Chemical treatment can yield complete detoxification for many of the more commonly used pesticides but is either ineffective or yields toxic by-products for many others. At the present time it is unlikely that chemical treatment could be instituted on a very wide scale or for very many pesticides. With additional research into treatment chemicals and conditions, it could become a very effective, although possibly somewhat limited, treatment method.

- Biological treatment is totally inappropriate for an individual applicator-operated treatment facility because of the nature of the waste, the operational difficulties encountered when working with microorganisms, and the expense.

- Adsorption is an effective method for removing most organic pesticides from water. High removal efficiencies can yield a relatively pesticide-free effluent which can be disposed of by conventional means. Adsorption is somewhat limited because of a requirement for pretreatment to remove suspended and inorganic materials and soils. In general, though, adsorption is sufficiently understood to recommend demonstration of applicator-operated adsorption units.

- Individual applicator-operated incinerators are considered infeasible; the systems are too expensive and require special operator skills to ensure complete combustion and no air pollution. On the other hand, centrally located hazardous waste treatment facilities containing incinerators could be a very effective, economic disposal option. At the present time, however, there are only a few such treatment facilities. Thus, the option is available to only a few pesticide applicators.

- Given the current state of the disposal method technology and the nature of the dilute pesticide solutions and their generation, only soil mounds could be widely implemented without further extensive research and with a minimum of environmental degradation expected. Evaporation basins and soil pits could be readily implemented in areas where the potential air quality degradation would be minimal. Small-scale carbon adsorption units for dilute pesticide solutions are considered technically feasible and should be demonstrated. Chemical treatment and land cultivation possess high potential as effective treatment methods but both have severe limitations. Further research is recommended to more fully identify these limitations and to establish the conditions under which each could be used most effectively and safely.

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